LOWER EXTREMITY KINETIC CHAIN DURING LOCOMOTION AND LANDINGS: RELATIONS TO MECHANISMS OF KNEE INJURY

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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TABLE OF CONTENTS

Abstract of Dissertation Presented to the Graduate School
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Knee injuries can result from repetitive impacts to the lower limb such as those observed during running or from a single impact as observed when landing from a jump. This two-part study investigated (1) motions of the lower extremity joints and forces transmitted to these joints when landing from a jump in prepubescent and postpubescent female athletes and (2) coordination of the lower extremity joints during the dissipation of impact forces transmitted to the body during locomotion and landings from a hop and a jump.

In Study I, 16 prepubescent and 16 postpubescent female athletes performed a series of six different jump-landing combinations. The results of this investigation indicated that the prepubescent athletes landed in a slightly more flexed position (knee flexion and ankle dorsiflexion, used less time and range of motion to dissipate the impact forces, and used greater eccentric muscle power than the postpubescent athletes when performing the different jump-landing combinations. The significant maturation by jump

type interactions observed for various dependent variables indicated that the two groups respond differently depending on the nature of the jump-landing activity. Whether these differences between the two groups are directly related to the increased incidence of injury warrants further research.

In Study II, 20 recreationally active female participants performed walking, jogging, hopping and jumping trials to investigate the degree of coordination between foot motions and rotations of the tibia during different sporting tasks. The ratio of foot movement to tibial rotation was found to change from the locomotion to the landing trials. This indicates that with the increased demands of the activity, the requirements of foot motion increased. However, this increased motion was not translated into rotation of the tibia at the subtalar joint as previously thought. Further, the correlative relationships between motions of several lower extremity joints were altered as the demands of the activity increased, indicating that the subtalar joint does not function as a fixed universal joint. This may have direct implications on clinical treatments aimed at controlling knee motion via controlling motion at the foot.

CHAPTER 1
INTRODUCTION

Physical activity and sport have become important aspects of daily life in our society. Since governmental legislation mandated that federally funded institutions provide organized opportunities for all individuals, women's participation in athletics has increased. Further, the greater variety of sports to choose from, the increased number of teams to compete on, and the abundance of practices and games have resulted in an increase in the number of hours a female athlete may participate each year. The increased number of participants at all age levels and the greater number of hours of exposure have been accompanied by growing concern in the sports medicine community regarding the increasing incidence of lower extremity injuries in this population. Though the overall frequency of musculoskeletal injury is similar between women and men for comparable sports, there is a substantially greater incidence of knee injuries (up to 8 times greater) in female athletes (Harmon & Ireland, 2000; Huston, Greenfield, & Wojtys, 2000; Kirkendall & Garrett, 2000).

Most knee injuries in female athletes occur in jumping and cutting sports such as volleyball, basketball, and soccer. Injury reports from female basketball and volleyball players have indicated that knee joint injuries account for over 60% of all injuries and are associated with more lost time from sports participation than most other orthopedic conditions (Briner & Kacmar, 1997; Gerberich, Luhmann, Finke, Priest, & Beard,1987; Gray et al., 1985; Solgard et al., 1995). Gray et al. (1985) reported that nearly 60%

of injured athletes were injured while landing from a jump, with the primary mechanism being landing and twisting upon impact while the lower extremity dissipates extremely high ground reaction forces. During ballistic activities such as running and landing from a jump, the actions of ankle dorsiflexion, knee flexion, and subtalar joint (STJ) pronation occur concurrently and are associated with attenuation of the impulse shock load. Researchers have hypothesized that asynchrony in the timing or magnitude of the motion between the knee, STJ and the ankle may lead to an antagonistic relationship and increased susceptibility to knee injury (Stergiou, Bates, & James, 1999). Surprisingly, no attempt has been made to investigate the coupling of motion between the foot and the knee during landing from jumps. Furthermore, factors that may influence this coupling relationship such as speed of locomotion or landing technique also warrant further research.

Improper movement coupling between the foot and shank as well as excessive foot motion have been implicated as being contributory to a number of lower extremity disorders (Clement, Taunton, Smart, & McNicol, 1981; Donatelli, Hurbert, Conway, & St. Pierre, 1988; James, Bates, & Osternig, 1978; Stergiou et al., 1999). Specifically, the transfer of movement from the foot to the shank, creating internal tibiofemoral rotation, has been theorized to increase the rotary stress at the hip and knee (Tibero, 1987). Indeed, excessive internal tibiofemoral rotation is the most reported mechanism leading to a complete rupture of the anterior cruciate ligament.

Forces transmitted to the body differ at various stages of maturation due to the development of body size, strength, and performance techniques and the changing nature of the sport activity as age increases (DeHaven & Linter, 1986). Interestingly, there is a

steady increase in the frequency of knee injuries including patellofemoral pain, internal knee derangement, and ligamentous sprains of the knee as females progress from age 13 to 25 years. Though epidemiological and experimental evidence suggests that postpubescent participants are more likely to be injured and that landing from a jump is a common mechanism of injury regardless of age, few studies exist investigating the mechanics of landing in these age groups or comparisons across age groups (McNair & Prapavessis, 1999; Sigg, Belyea, & Ives, 2001).

In summary, landing from a jump is a common mechanism for knee injury resulting from the large forces that must be absorbed by the lower extremity. Previous research on the lower extremity during landings has focused on the prediction of impact forces (Dufek & Bates, 1990) and the influence of manipulating landing technique (Devita & Skelly, 1992). Further studies evaluated how skill level (McKinley & Pedotti, 1992) and landing surface (Dufek & Bates, 1991) affect lower extremity mechanics, while others have manipulated the landing distance, drop height and technique (McNitt-Gray, 1993; Zhang, Bates, & Dufek, 2000). Primarily, these investigations examined movement in the sagittal plane to identify factors related to a potentially dangerous landing performance. However, previous studies had failed (1) to evaluate the coordinative action of the lower extremity joints and (2) to investigate interventions aimed at controlling transverse plane rotations during landing. Though the likelihood of injury increases as female participants mature past puberty, little is known about the interaction between maturation and landing strategy in female sports participants. Therefore, the aims of this study were: (1) to identify landing strategies and mechanics in prepubescent and postpubescent females during six different types of jumps and (2) to

study relationships among the movements of the foot, ankle, and knee during locomotion and while performing different landing techniques. Specifically, this study investigated the relative motions between adjacent segments of the lower extremity and identified whether these motions are influenced by the demand of the activity (i.e., locomotion vs. landing). It was hypothesized that postpubescent athletes would land in a manner that would predispose them to knee injury; thus, GRF, moments, and powers would be significantly greater than in the prepubescents. Further it was hypothesized that as the loading demands of the activity increases there would be a significant increase in the coupling of motion between the lower extremity joints.

The variables to be examined in these studies are summarized in Figure 1-1. It is expected that the findings may provide information for understanding lower extremity injuries related to jumping activities for females. Such information may be useful to physicians, therapists, trainers, coaches, military, and exercise professionals when designing programs and interventions to reduce the likelihood of injury in this population.

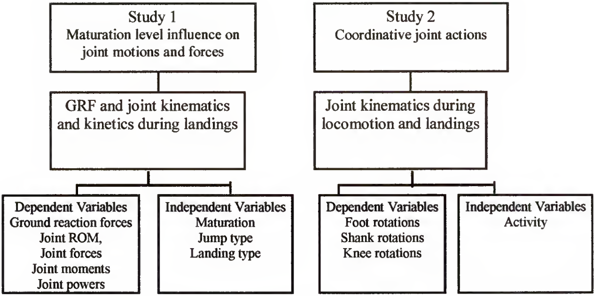


Figure 1-1. Flow chart of the two study investigation.

CHAPTER 2
REVIEW OF LITERATURE

Increased participation by females in sporting activities has been accompanied by an increased incidence of injury. Overall, the frequency of athletic injuries among females is nearly equal to that among males in a given sport. However, females are substantially more susceptible to knee injuries (Harmon & Ireland, 2000; Huston et al., 2000; Kirkendall & Garrett, 2000). Injury epidemiology data also suggests that female athletes are more likely to be injured as they progress through puberty and increase their participation in organized competitive sports (Backx, Erich, Kemper, & Verbeek, 1989; DeHaven & Linter, 1986). The majority of knee injuries occur in jumping and cutting sports such as soccer, basketball, and volleyball. In these sports, the jump-landing sequence has been identified as a common mechanism of knee injury (Gray et al., 1985). During a landing, the lower extremity joints must function simultaneously to attenuate very large impact forces. A lack of coordination between subtalar and knee joint actions has been suggested as a potential mechanism for lower extremity injuries (Stergiou et al., 1999). The purpose of this review is to summarize the relevant information regarding subtalar and knee anatomy, injury epidemiology, mechanisms of knee injury, and potential factors related to knee injury--subtalar and knee joint motions and landings.

Subtalar Joint Anatomy

The subtalar joint is a composite joint comprising three planar articulations between the superior calcaneous and the inferior talus (Figure 2-1). The three articulating

surfaces allow for triplanar movement about a single oblique axis permitting one degree of motion: pronation and supination. The subtalar joint axis passes through the talus and extends from below on the lateral side of the heel, upward, forward, and medially (Inman, 1976; Manter, 1941). Manter (1941) found that the axis inclined 42° upward and anteriorly from the transverse plane and directed medially 16° from the sagittal plane. Because the axis is nearly halfway between horizontal and vertical, the component motions of eversion/inversion (horizontal) and adduction/abduction (vertical) are about equal in magnitude. In weight bearing, subtalar supination is composed of abduction and dorsiflexion of the talus and inversion of the calcaneus. Conversely, pronation is composed of calcaneal eversion and talar plantarflexion and adduction. The combined motions of pronation and supination allow the foot to adapt to the terrain, dampen rotational forces imposed by body weight, and allow the foot to act as a rigid lever for propulsion (Norkin & Levangie, 1992).

Knee Joint Anatomy

The knee, located between the two longest levers in the skeletal system, is one of the most complex joints in the body (Figure 2-2). Composed of the tibiofemoral and patellofemoral joints, the knee transmits loads, participates in locomotion, aids in the conservation of momentum, and provides a force couple for activities involving the lower limbs (Nordin & Frankel, 1989). Despite these demanding functions, the bony geometry of the knee provides little stability (Irrgang, Sarfran, & Fu, 1996). Thus, the integrity of the knee joint is supplied by the static and dynamic restraints provided by the menisci, joint capsule, ligaments and muscles crossing the joint.

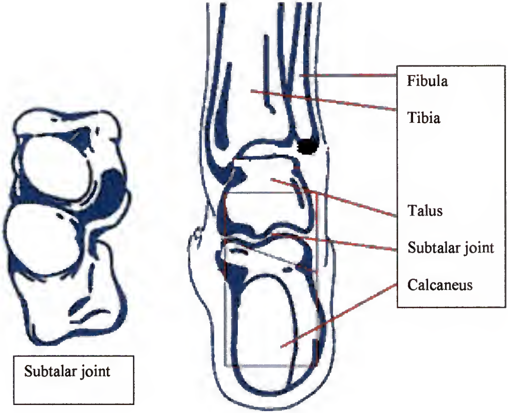


Figure 2-1. Rear view of the subtalar joint complex (Norkin & Levange,1992).

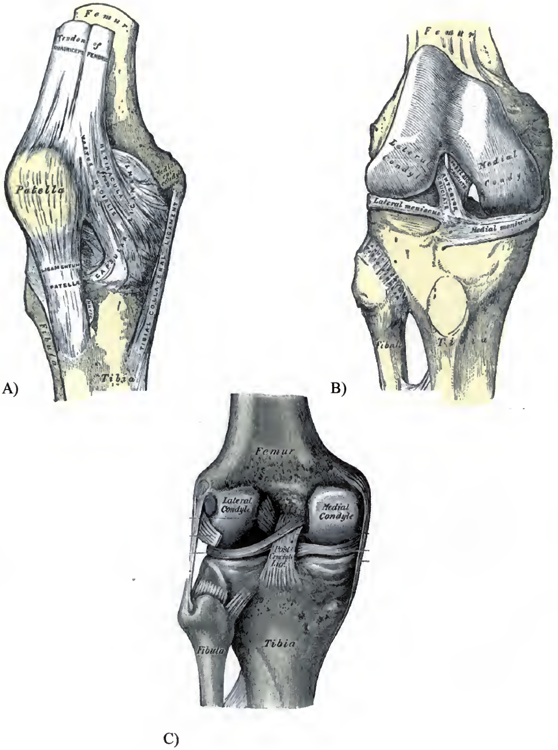


Figure 2-2. The knee joint complex. A) Anterior view of knee joint complex. B) Anterior view of the knee with the patella removed. C) Posterior view of the knee (Gray,1995).

The primary ligamentous restraints of the knee are the collateral and cruciate ligaments. The medial collateral ligament (MCL) resists valgus forces that tend to distract the medial compartment of the tibiofemoral joint; whereas, the lateral collateral ligament (LCL) resists varus forces that tend to cause separation in the lateral compartment. The posterior cruciate ligament (PCL) is the primary restraint to posterior translation of the tibia with respect to the femur. Conversely, the primary stabilizer of the knee, the anterior cruciate ligament (ACL), restrains anterior displacement of the tibia relative to the femur. It also stabilizes the tibia against abnormal internal tibiofemoral rotation and serves as a secondary restraint against a varus and valgus stress (Irrgang et al., 1996). Ligaments provide passive stability to movement, while the muscles serve as an active restraint. The tension developed in the patellar tendon due to quadriceps contraction attempts to displace the tibia anteriorly. However during dynamic activity, co-contraction of the hamstrings works synergistically with the ACL to prevent this quadriceps directed anterior tibial displacement. Draganich and Vahey (1990) demonstrated that co-contraction of the hamstrings significantly decreases the strain on the ACL. However, the orientation of the hamstring muscles relative to the knee prevents them from protecting the ACL against anterior directed forces near the end range of knee extension (Wilk, Arrigo, Andrews, & Clancy, 1999).

Injury Epidemiology

The increase in athletic participation by women has increased the awareness of medical issues related to the female athlete. Specifically, during the last 15 years, significant emphasis was placed on the injury rate in female participants of all ages. Backx et al. (1989) surveyed sports injuries in 7,468 pupils aged 8 to 17 years and

reported twice as many injuries in the group of females aged 13-16 years as in the females aged 8-12 years. Similarly, DeHaven and Linter (1986) evaluated 3,431 cases of athletic injuries for differences among gender, sport, and age group. They reported that the highest percentage of patients (45% of all cases) were between the ages of 16 and 19 years followed by those in the 20-25 year-old group (25%), while patients under 13 years of age represented only 3% of the injuries. Interestingly, from ages 13-25 years the frequencies of patellofemoral pain, internal knee derangement, and ligamentous sprains of the knee accelerated. Further, reports produced by the National Collegiate Athletic Association and the National Federation of State High School Association showed that twice as many serious knee injuries occur in high school female athletes as in their collegiate counterparts (Hewett, 2000).

Injury epidemiology studies also focused on identifying sports and activities within these sports, that are likely to cause injury. The majority of injuries found in football, basketball, volleyball, and soccer occur in the lower extremity with the knee being particularly vulnerable (Briner & Kacmar, 1997; Gerberich et al., 1987; Gray et al., 1985; Solgard et al., 1995). DeHaven and Linter (1986) reported that injuries are more concentrated about the knee joint in females. In fact, the knee was the most injured site in females representing 60% of all injuries. Knee MCL and ACL sprains were the most common sprains encountered in females. Gray et al. (1985) reported that 58% of all injured basketball players were injured while landing from a jump. Specifically, knee joint injuries accounted for 72% of these injuries. The jump-landing sequence is also the most common source of injury in volleyball: most (90%) of injuries occurring in the lower extremity with the knee joint being particularly vulnerable (Briner & Kacmar,

1997). Injuries to the knee joint are especially debilitating because they are associated with more lost time from sports participation than other orthopedic injuries (Solgard et al., 1995). Perhaps the most serious knee injury resulting from landing is a rupture of the ACL.

In recent years, ACL injury has become a primary concern for the sports medicine community. As mentioned, the injury rate for females is substantially higher than that of their male counterparts. Malone, Hardaker, Garret, Feagin, and Basset (1993) reported that female collegiate basketball players were eight times more likely to sustain ACL tears compared to male collegiate basketball players. Lidenfeld, Schmitt, Hendy, Mangine, and Noyes (1994) reported that the injury rate for ACL injuries in female soccer players was six times greater than that of their male participants. Wilk et al. (1999) reported that female high school athletes have a 1 in 100 chance of sustaining ACL injury while male high school athletes appear to have a 1 in 500 chance. This likelihood of injury occurrence is even more alarming at the collegiate level where female athletes appear to exhibit a 1 in 10 chance, while the men have a 1 in 50 chance. It is important to note that, though a greater number of injuries occur in high school participants, the likelihood of injury is higher in the college participants. Several research investigations have attempted to elucidate the differences between men and women that have led to this disparity in incidence rates. Most of these studies have documented intrinsic differences between the sexes, however, the relationship between these intrinsic variables and known mechanisms of injury remains unclear.

Mechanisms of Injury

The majority of injuries to the ACL are noncontact in nature. Information attained from experimental loading studies and observational evidence led to the identification of several mechanisms of ACL injury. The two primary mechanisms of ACL injury involve a combination of valgus knee position and lower extremity external rotation and a combination of knee flexion and internal rotation (Ireland, 1999; Jarvinen, Natri, Laurilla, & Kannus, 1994). Hess, Rupp, Hopf, Gleitz, and Liebler (1994) studied 151 sports-related ACL injuries and reported that internal tibiofemoral rotation on a flexed knee was the most common mechanism of injury. Fu and Stone (1994) noted that most noncontact ACL injuries in the sports of soccer, football and skiing, occurred with the tibia in external rotation and the knee in valgus. Conversely, in basketball, an ACL injury most often occurs when the knee is hyperextended and the tibia is internally rotating. Excessive internal tibial rotation with respect to the femur places high biomechanical demands on the knee joint and its internal structures. Specifically, excessive internal rotation of the tibia increases the distance between the attachment sites of the ACL producing tension in the ligament (Ahmed, Burke, Duncan, & Chan, 1992). An anterior shear force coupled with an internal rotational torque of the tibia on the femur has been identified as the most detrimental combination of loads (Emerson, 1993).

Factors Related to Injury

Movement Coupling of the Lower Extremity. Movement coupling has been used to describe how much movement occurs about one axis of rotation relative to a simultaneous rotation about a second axis (Stacoff et al., 2000). Ankle motions during locomotion have been extensively investigated by a movement coupling perspective.

Specifically, coupling between foot eversion and internal tibial rotation has received the most attention. Levens, Inman, and Blosser (1948) and Wright, Desai, and Henderson (1964) both concluded that the tibial rotation must be resolved at the subtalar joint. Moreover, Lundberg (1989) substantiated the existence of a rotation transfer mechanism when he found that moving the foot from pronation to supination induced transverse plane rotation of the tibia.

Movement coupling between foot inversion/eversion and tibial rotation was described in more recent investigations. Nigg, Cole and Nachbauer (1993) investigated the effects of arch height of the foot on angular motion of the lower extremity in running. Linear regression analyses revealed that the arch height did not influence either the maximal eversion movement or maximal internal leg rotation. However, the transfer of foot eversion to internal leg rotation was found to increase significantly with increasing arch height. The authors concluded that the extremely high correlation of .99 supports the assumption that foot eversion is coupled to internal rotation of the tibia during the first half of the running stance.

McClay and Manal (1997) investigated whether differences exist in the coupling of foot and knee motions during the support phase of running in subjects with normal rearfoot motion and those who pronate excessively. Timings between peak knee and rearfoot angles were not significantly different between groups, though times were more closely matched in the normal subjects. The eversion to tibial internal rotation excursion ratio was significantly lower in the pronated subjects. The mean eversion/tibial internal rotation ratio across all subjects was 1.38. Correlation analyses revealed significant relationships among the following parameters: ankle dorsiflexion-knee flexion (.75), foot

eversion and both knee internal rotation (.58) and tibial internal rotation (.43) across both groups and between eversion and knee flexion (.67) in the normal group. The pronated subjects exhibited significantly greater tibial internal rotation and dorsiflexion and possessed a significantly lower eversion/tibial internal rotation ratio than the normal subjects. The authors concluded that increased motion of the rearfoot can lead to excessive movement at the knee. Furthermore, they suggested that excessive pronation may disrupt the normal kinematic interaction between the rearfoot and the knee.

Stergiou and Bates (1997) suggested that a lack of coordination between the subtalar and knee joint actions is likely to occur when a bimodal rearfoot angle curve is coupled with the typical unimodal knee angle curve. A unimodal rearfoot curve is defined as a parabolic curve with a single minimum, whereas a bimodal curve exhibits two minimums with a local maximum in between. Further, they suggested that increases in impact forces may augment the abnormal timing between the two joint actions and may disrupt their coordinative motions. To test these hypotheses Stergiou et al. (1999) had subjects running at different speeds (self selected, 10% faster, 20% faster, and 10% slower) and over obstacles of different heights (5%, 10%, and 15% of their standing height). The results indicated that the GRF and differences between rearfoot and knee angular velocities increased with increasing speed and obstacle height. The rearfoot angle curve also changed from a unimodal to a bimodal parabolic configuration. These findings led the authors to suggest that a possible mechanism responsible for running injuries is the lack of coordination between the actions of the subtalar and knee joints.

Reischl, Powers, Rao, and Perry (1999) examined the relationship between whole foot pronation and rotation of the tibia and femur during walking in 30 subjects

demonstrating a wide range of pronation. Regression analysis revealed that the magnitudes and timings of whole foot pronation were not predictive of the magnitudes and timings of tibial and femoral rotations. Further, the magnitude of tibial rotation was not predictive of the magnitude of femoral rotation but the timing of tibial rotation was predictive of the timing of femoral rotation. The lack of association between these variables led the authors to suggest that a specific lower extremity kinematic pattern cannot be inferred by assessing the mechanics of the entire foot.

Recently, Stacoff et al. (2000) investigated movement coupling at the ankle during the stance phase of running using bone-mounted markers. Movement coupling was observed in all subjects with considerable individual differences. Eversion and internal tibial rotation took place between heel strike and midstance followed by inversion and external tibial rotation. These general patterns were consistent for all subjects. Coupling coefficients, defined as the ratio of tibial rotation over eversion, averaged .58 from heel contact to foot flat and .46 from midstance to toe off. This led the authors to suggest that the subtalar joint is not a direct coupler and does not function as a "universal joint".

Movement coupling between subtalar motion and knee flexion, subtalar motion and tibial rotation, and subtalar motion and knee rotation has been studied in locomotion for a number of years. These coupling relationships were found to depend on the vertical load, the degree of dorsiflexion / plantarflexion ligament integrity and muscle-tendon forces. However, these relationships have not been investigated in landing tasks. During a landing, the subtalar and knee joints must function effectively together to attenuate the impact forces or an injury may occur.

Landing. Landing technique has significant implications on the kinematics of the lower extremity joints, muscle activation patterns, and GRF values (Devita & Skelly, 1992). Dufek and Bates (1991) suggested that high GRF are strongly related to high risk of knee injury. Several studies have investigated sagittal plane motion of the lower extremity during various landing tasks.

Mizrahi and Susak (1982) examined the influences of drop height and landing techniques on the vertical GRF generated during landing. Toe-heel landings from a 0.5 m drop resulted in mean vertical ground reaction forces from 1.67-2.75 times the body weight (BW) and 1.69-4.17 BW for the first and second peak forces, respectively. From a 1.0 m drop, the first and second mean peak vertical GRF increased ranging from 2.98-5.60 BW and 2.83-5.55 BW, respectively. Flat foot landings from the same heights created vertical GRF ranging from 1.82 to 6.18 BW. The authors concluded that increasing landing height caused the participants to exhibit greater range of motion in the lower extremity joints and created greater vertical GRF.

Valiant and Cavanaugh (1985) investigated two different landing techniques (forefoot-rearfoot and flat-footed) during rebounding in basketball in an attempt to improve shoe design. Two peak forces were observed during the forefoot-rearfoot landing that occurred when the forefoot and rearfoot contacted the ground, respectively. They reported average vertical GRF values of 1.3 BW and 4.1 BW for the forefoot and rearfoot contacts. Conversely, flat-footed landings created only one peak vertical GRF, which was generally a larger value averaging 6.0 BW. The authors concluded that the shoe should be designed to accommodate the conditions of flat foot landing, which was the more severe of the two cases. Gross and Nelson (1988) also examined the shock

attenuation role of the ankle during landing from a vertical jump. They reported that forefoot landings effectively reduced the landing impact.

Stacoff, Kaelin, and Steussi (1988) investigated landing mechanics during landing from a spike in female volleyball players. They observed the first and second impact forces, associated with forefoot and heel contacts, ranging from 1,000 to 6,500 N. Further, they reported an inverse relationship between the magnitude of rearfoot and forefoot impact values. As the GRF associated with forefoot contact increased the corresponding values decreased as the rearfoot made contact with the ground. These findings led the researchers, Kaelin, Stacoff, Denoth, and Steussi (1988), to evaluate the effects of different shoe characteristics in landing from a drop height of 0.45 m. Though only one participant performed the landing, it was found that softer shoe construction resulted in a 3.3% reduction in the peak forefoot vertical GRF and an 18% reduction in rearfoot vertical GRF values.

Miller and Nissinen (1987) observed peak vertical GRF values of 13.6 BW for nine male gymnasts for the first maximum force and 6.1 BW for the second maximum force in landings from a running forward somersault. Similarly, Panzer and colleagues (1988) investigated the landing phase of a double back somersault by competitive gymnasts. They reported peak vertical GRF values ranging from 8-14 BW. The authors concluded that a technique which allowed for greater knee flexion produced greater compressive and shear loads transmitted to the knee and hip joints. This finding is contrary to the results reported by Nigg (1977) who reported that greater knee flexion during landing reduced the vertical forces transmitted up the lower extremity kinetic chain.

The effects of landing stiffness on the kinetic responses of the lower extremity were studied by Devita and Skelly (1992). The variables investigated were angular joint displacement, GRF, work done, moments and powers of the lower extremity joints. Interestingly, the shape of the GRF, moment and power curves were identical between the soft (averaging 117° of knee flexion) and stiff landing (averaging 77° of knee flexion) techniques. Conversely, the vertical GRF values and the ankle plantarflexor moments were significantly larger in the stiff landings. This finding was similar to that reported by Dufek, Caster, and Bates (1989) who examined different drop landing heights, distances and landing technique. They reported that the first peak, second peak, maximum braking, and maximal propulsive forces were significantly greater in magnitude in the stiff landing condition.

More comprehensive kinetic analyses of landings were performed by Simpson and colleagues (1997a; 1997b) who investigated knee joint forces during landings from traveling jumps in professional dancers. Each participant performed 10 trials at 30, 60, and 90% of their maximal horizontal jump distance. As the jump distance increased, greater peak vertical GRF, knee flexion, knee and ankle flexion velocities, tibial landing angle, net maximal knee and ankle joints moments, ankle and knee axial and shear forces were observed. The maximal ankle and knee axial forces averaged 91.8 N/kg and 164.9 N/kg, respectively, whereas the maximal shear forces averaged 10.9 N/kg and –18.5 N/kg, respectivley.

Schot, Dufek, and Bates (1991) investigated the relative contributions of the ankle, knee, and hip to shock absorption during drop landings from a 60 cm platform. The authors identified three unique landing styles and classified them as soft, medium, or

hard based on the observed peak vertical GRF and the angular excursions of the lower extremity joints. They concluded that the knee and ankle joints acted as the primary functional shock absorbers and the hip was identified as a secondary shock absorber.

The kinetics of the lower extremities during drop landings from three different heights (0.32, 0.72, 1.28 m) were investigated by McNitt-Gray (1993). The analyses concentrated on the time from the initial contact until the lowest vertical position of the center of gravity. Increasing drop heights resulted in concurrent increases in maximum extensor moments and extensor muscle work.

In a follow-up investigation, McNitt-Gray, Yokoi, and Millward (1994) tested the effects of landing surface on drop landings from a 0.69 m platform in gymnasts. Ten female and four male gymnasts performed barefoot landings onto a stiff mat, soft mat, and force platform surfaces. As surface stiffness increased, the time to peak vertical GRF decreased. Conversely, as landing surface stiffness decreased, lower peak vertical GRF, longer landing phases, and greater hip and knee flexion angles were observed.

Dufek and Zhang (1996) evaluated the lower extremity landing performance of elite volleyball players longitudinally. Subjects were analyzed while performing block-jumps during the off-season, in-season, and post-season. They evaluated three dependent variables that characterized the impact: first (F1) and second (F2) peak vertical GRF, and knee joint range of motion. No significant differences were found in the GRF data. Values of F1 and F2 averaged 10.19 and 22.8 N/kg, respectively, across the three testing conditions. However, the results indicated that a significant kinematic change in landing performance occurred across the season as the knee range of motion from the time of F1

to F2 was less in the off-season. The authors suggested these kinematic differences have implications for training and assessment of these individuals.

The influence of landing position on lower extremity mechanics was studied by Kovacs et al. (1999) who compared lower extremity kinematics and kinetics between drop vertical jumps performed with heel-toe and forefoot landings. The first and second peak vertical GRF were 3.4 times and 1.4 times lower for the heel-toe landing compared to the forefoot landing. During the landing phase of the heel-toe pattern, the hip and knee joints contributed 40% and 45% to the total torque, respectively, whereas during fore-foot landings the ankle and knee both contributed 37% of the total torque. The authors concluded that foot placement strategy modifies both the landing forces and the individual joint contributions to total torque during drop jumping.

Recently, Zhang, Bates, and Dufek (2000) investigated the changes in lower extremity joint energy absorption for different landing heights and landing techniques. Participants performed step-off landings from three different heights (0.32, 0.62, 1.03 m) using soft, normal and stiff landing techniques. Increasing step-off height and landing stiffness resulted in greater GRF, peak joint moments, and powers. The knee joint was a consistent contributor to energy dissipation regardless of height or stiffness, whereas the ankle plantarflexors contributed more in the stiff landings and the hip contributed more during soft landings. Further, a shift from ankle to hip strategy was observed as the landing height increased.

Summary

Female athletes experience knee injuries at an alarming rate and the likelihood of injury increases as participants mature past puberty. Several researchers have reported

that the majority of knee injuries occurred during the landing from a jump. Some injuries may occur as the tibiofemoral joint is exposed to considerable loads during landing activities because of the transmission of GRF that are nearly 5-6 times those seen in normal walking (Winter & Bishop, 1992). Asynchrony in the shock absorbing motions of foot pronation, tibial rotation and knee flexion may explain the increased susceptibility of injury around the knee joint. Though maturation, landing from a jump, and coordinative action of the lower extremity joints are all related to knee injury, previous research has not investigated the interaction among these variables. Thus, a comprehensive analysis of the lower extremity kinetic chain during different types of landing is warranted.

CHAPTER 3
DOES MATURATION LEVEL INFLUENCE LOWER EXTREMITY MOTION AND FORCES DURING LANDINGS?

Lower extremity skeletal alignment has been implicated as a possible factor leading to a greater ACL injury rate in females compared to their male counterparts (Harmon & Ireland, 2000; Huston et al., 2000; Kirkendall & Garrett, 2000). Specifically, structural alignments such as: excessive Q-angle, thigh foot angle, genu recurvatum, femoral anteversion, smaller intercondylar notch width, decreased notch width index, and generalized joint laxity have been related to increased likelihood of injury (Harmon & Ireland, 2000; Loudin, Jenkins, & Loudin, 1996). However, a majority of these structural variations develop only after the rapid growth associated with puberty. Not surprisingly then, females are more likely to be injured after the onset of the growth associated with puberty.

At various stages of maturation, forces transmitted to the body are different due to development of size, strength, and the changing nature of the sport activity as age increases (DeHaven & Linter, 1986). Backx et al. (1989) surveyed sports injuries in 7,468 pupils aged 8 to 17 years and reported twice as many injuries in the group of females aged 13-16 years as in the females aged 8-12 years. Similarly, DeHaven and Linter (1986) evaluated 3,431 cases of athletic injuries for differences among gender, sport, and age group. They reported that the highest percentage of patients (45% of all cases) were between the ages of 16 and 19 years followed by those in the 20 to 25-year-old group (25%), while patients under 13 years of age represented only 3% of the

injuries. Interestingly, from ages 13-25 years the frequencies of patellofemoral pain, internal knee derangement, and ligamentous sprains of the knee accelerated. Reports produced by the NCAA and the National Federation of State High School Association indicated that twice as many serious knee injuries occur in high school female athletes compared to their collegiate counterparts, though the likelihood of injury is greater in collegiate athletics (Hewett, 2000).

The majority of injuries to participants in basketball, volleyball, and soccer occur in the lower extremity with the knee being particularly vulnerable (Briner & Kacmar, 1997; Gerberich et al., 1987; Gray et al., 1985; Solgård et al., 1995). DeHaven and Linter (1986) reported that injuries were more concentrated about the knee joint in females. Indeed, the knee was the most injured site in females representing 60% of all injuries with MCL and ACL sprains the most common sprains encountered.

Several reports indicate that the majority of non-contact knee injuries occur during cutting maneuvers or landing from a jump (Harmon & Ireland, 2000; Huston et al., 2000; Kirkendall & Garrett, 2000). Jumping and landing movements are integral features of many sporting activities and have been investigated by many researchers. The research on landing has concentrated on the implications of impact and the resulting loads placed on the lower extremity and the injury potential of various landing situations (Devita & Skelly, 1992; Dufek & Bates, 1990; Dufek & Bates, 1991; Gross & Nelson, 1988; James, Dufek, & Bates, 2000; Kovacs et al., 1999). Though epidemiological and research evidence suggests that postpubescent participants are more likely to be injured and that landing from a jump is a common mechanism of injury, few studies exist

investigating the mechanics of landing in these age groups or comparisons across age groups.

Sigg et al. (2001) reported significant differences in landing force across age and gender in elementary school children in grades K-5. Children in the 5th grade, regardless of gender, exhibited a decrease in landing force compared to all other grades. Across all grades, females produced significantly less vertical GRF than their male counterparts during maximal vertical jumps (2.34 BW vs. 2.45 BW). Conversely, McNair and Prapavessis (1999) showed no significant differences in peak vertical GRF across genders, activity levels, or types of sport investigated when landing from a 30 cm high box in adolescents (mean age: 16 years). Based on only GRF it is very difficult to determine whether the inconsistent findings reported in the two studies are due to differences in jump heights or different landing strategies.

Female athletes are more likely to be injured as they progress through puberty and increase their participation in organized competitive sports. The jump-landing sequence is a common maneuver performed in sports for all ages and has been identified as a common mechanism of knee injury. Currently, there is a lack of information regarding the interaction between maturation and landing strategy in female sports participants. Thus, the purpose of this investigation was to identify landing strategies and lower extremity mechanics in prepubescent and postpubescent females. Specifically this investigation compared lower extremity joint kinematics, the GRF, joint resultant forces, moments and power of prepubescent and postpubescent females during six different jump-landing tasks. The results may provide information for understanding lower extremity injuries related to jumping activities for females.

Methods

Participants

Sixteen recreationally active women ranging in age from 18-25 years were recruited from graduate and undergraduate classes at the University of Florida. Additionally, 16 recreationally active girls ranging in age from 8-11 years were recruited from the surrounding community. All participants regularly performed jump-landing movements as components of their exercise and sports activities. Participants from a variety of athletic backgrounds (e.g., basketball, soccer, volleyball, gymnastics, dance and running) were tested. These individuals were free from any orthopedic or neurologic conditions that influence lower extremity mechanics. Characteristics of the participants can be found in Table 3-1.

Instrumentation

The kinematic and kinetic characteristics of landing were evaluated using video-based motion analyses and a force platform. Frontal and sagittal views of the body were obtained for all trials using two high-speed video cameras collecting at 250 Hz (SR 500 Kodak Motion Corder Analyzer; Eastman Kodak Corporation, San Diego, CA). A Bertec force platform (Bertec Corporation, Columbus, Ohio) sampling at 1000 Hz was used to obtain GRF data and served as a landing area and a trigger for video acquisition (Figure 3-1). The sampling of GRF and video recording was initiated 100 ms prior to initial contact and continued for 500 ms. High-speed video and GRF data were analyzed using a Peak Motus motion analysis system (Peak Performance Technologies, Englewood, CO). Anthropometric measurements were made using an anthropometer (Seritex Inc., New York, NY). The maximal vertical jump height of each participant was measured using a

Table 3-1. Characteristic information for test participants

Characteristic		PRE	POST
N		16	16
Age (yr)	Mean	9.0	20.2
	SD	1.0	1.2
Mass (kg)	Mean	33.1	58.5
	SD	9.2	7.2
Height (cm)	Mean	134.5	162.6
	SD	9.1	6.09

Note: PRE: prepubescents; POST: postpubescents.

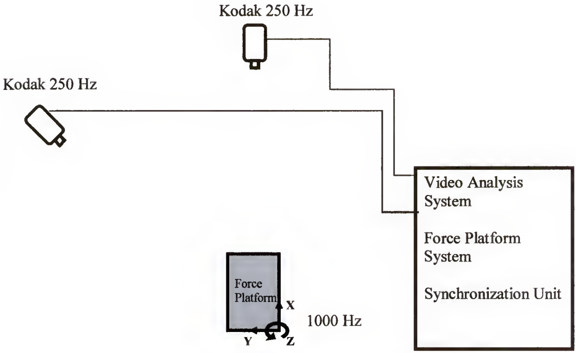


Figure 3-1. An overhead view of the experimental set up.

Just Jump mat (Probotics, Inc., Huntsville, AL) and horizontal stride jump distance was measured using a standard measuring tape.

Procedures

Before participation, each participant read and signed a written inform consent statement approved by the Institutional Review Board. Parental consent was obtained for the prepubescent participants prior to data collection. After the consent was given, participants were fitted with black tight-fitting shorts and were asked to remove their shoes and socks. At this point, a series of anthropometric measures were made including body mass, girths of the upper thigh and calf, and the breadths of the knee, ankle, and metatarsal heads and length of the foot. Using the protocol proposed by Gordon et al. (1989), the following measurements were made: stature, trochanteric height, tibial height, femoral length, tibial length, maleollar height, and bispinous breadth. To eliminate inter-rater variability the same investigator made all of the anthropometric measurements.

Upon the completion of the anthropometric measures, participants warmed up by walking for five minutes on a motorized treadmill. Following the initial treadmill warm-up, the participants performed three vertical jumps and three stride jumps (jump from one foot and land on the other) with maximal effort. The maximal vertical height and toe-to-heel horizontal displacements achieved during the jumps were recorded and used to determine the step-off heights and stride distance for the experimental session.

Participants were prepared for the jumping protocol by placing reflective markers over the 2nd ray, metatarsal head V, lateral malleolus, mid shank, lateral knee, lateral thigh, greater trochanter, and ASIS of the participant's dominant leg and the contralateral ASIS (Figure 3-2). Markers were placed in a manner similar to that described by

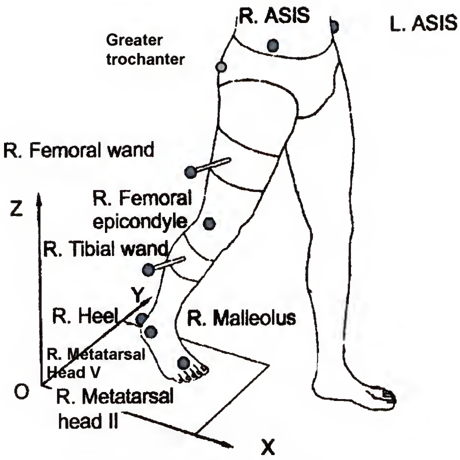


Figure 3-2. Location of marker placement and force plate coordinate system (Vaughn et al.,1999).

Vaughn, Davis, and O'Connor (1999). With this marker orientation, markers defined the local (moving) coordinate systems embedded in the thigh, calf and foot segments and were used to track segment motion (Figure 3-3).

Following the marker placement, each participant was instructed on how to perform the six different jumping-landing conditions. Practice trials were allowed for each condition to ensure consistent performance before performing the experimental jump-landings for data collection. The participant then performed a series of landings from all combinations of jump types (drop jump (DJ) and stride jump (SJ)) and landing sequences (static (S), vertical (V), and lateral (L)) with maximum effort. The six jump-landing combinations were performed in a random order. Drop jumps were initiated from a stationary platform, scaled to match each individual's maximal vertical jump height, with the dominant foot leading forward, the contralateral foot remaining in contact with the platform, and the center of mass as steady as possible before stepping off. Stride jumps were initiated from a fixed distance from the force plate, as the participant stood on the laboratory walkway with their dominant leg held in front of the body. During the static landing sequence for both jump types the participants were encouraged to land with their foot on the center of the force platform. Unsuccessful landings due to loss of balance, touching the floor with the contralateral limb, or a short additional hop upon landing were immediately repeated. The vertical and lateral landing sequences required the participants to jump with maximal effort in the vertical and lateral directions, respectively, upon making contact with the force platform. Participants performed two successful trials for each of the six jump-landing combinations (DJL, DJV, DJS, SJL, SJV, SJS) for a total of 12 trials.

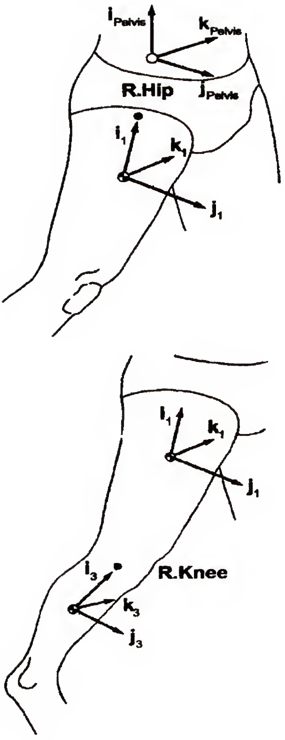


Figure 3-3. Location of anatomical coordinate systems (Vaughn et al., 1999).

Data Reduction

Each reflective marker was digitized and positional data were scaled and smoothed, using a fourth order Butterworth filter with an optimal cut-off frequency determined by the Jackson Knee Point Method (Jackson, 1979) and a commercial software package (Peak Performance Technologies Inc, Englewood, CO). The location and magnitude of the lower extremity segmental masses and their moments of inertia were estimated using mathematical models, averaged segmental masses, and the individual participant's anthropometric data as proposed by Vaughn et al. (1999) with the exception that the greater trochanter marker was used to predict the location of the hip joint center. Joint kinematic data were calculated as described by Vaughn et al. (1999). Joint reaction forces and joint moments of force were calculated for the lower extremity using an inverse dynamic analysis that combined the anthropometric, kinematic, and GRF data. The joint muscle power was calculated as the product of the joint moment and angular velocity.

Statistical Analyses

Descriptive statistics (Mean $\pm$ SD) were calculated for age, height, weight, and the anthropometric data. The variables of interest in this investigation included: joint positions of the hip, knee, and ankle at the instant of touchdown, joint ranges of motion defined as the change in angular position from the instant of touchdown to maximum knee flexion, time to maximum knee flexion, anterior/posterior GRF, magnitude and timing of the VGRF, peak anterior/posterior knee shear force, and peak resultant joint forces, moments, and powers of the hip, knee, and ankle. These dependent variables (kinematic and kinetic) were compared using two separate 2 x 2 x 3 (Maturation level x

Jump type x Landing sequence) MANOVAs with repeated measures on the last two factors. Separate univariate tests were performed for follow up testing when appropriate. An a-priori alpha level of 0.05, and an a-priori beta level of 0.20 was used in this study.

Results

Kinematics

The mixed design MANOVA (Maturation x Jump type x Landing sequence) revealed that the participants contacted the floor with different angular orientations of the hip, knee, and ankle joints in the two different jump type conditions ($p<0.05$). Compared to the stride jumps, the hip, knee, and ankle joints were 13.6°, 2.5°, and 10.2°, more extended during the drop jumps, respectively. The knee angle at touchdown was significantly more flexed in the prepubescents ($F(1,30) = 8.90$, $p = 0.006$) than in the postpubescents with an average difference of 4.5°. No significant two or three way interactions were detected for the angular orientation of the lower extremity joints at the instant of touchdown. Angular orientation of the hip, knee, and ankle joints during the six different jump-landings can be found in Table 3-2.

The mixed design analysis yielded a significant landing sequence effect for the time to maximum knee flexion ($F(2,60) = 7.94$, $p = 0.008$). Post-hoc analysis revealed that the time to maximum knee flexion significantly increased from the static to the vertical and from the vertical to the lateral landing sequence conditions. There was also a trend for the prepubescents to reach maximum knee flexion faster than the postpubescents ($p = 0.07$) averaging 30 ms faster. No significant differences in the time to maximum knee flexion were detected between the jump types and no significant interactions were observed. The time to maximum knee flexion during the six different jump-landing sequences can be found in Table 3-3.

Table 3-2. Mean angle (°) of the lower extremity joints at the instant of touchdown.

	DJL	DJV	DJS	SJL	SJV	SJS
Hip						
PRE						
Mean	118.0°	115.3°	118.2°	101.9°	103.2°	104.4°
SD	11.0°	9.2°	8.8°	14.3°	13.9°	13.0°
POST						
Mean	117.6°	118.0°	119.0°	102.5°	105.3°	107.3°
SD	6.8°	7.0°	7.0°	14.3°	11.0°	12.9°
Knee						
PRE						
Mean	160.1°	160.4°	160.7°	157.7°	157.8°	158.5°
SD	4.7°	4.8°	5.7°	6.5°	5.9°	6.7°
POST						
Mean	164.5°	164.8°	165.4°	161.1°	163.1°	163.1°
SD	3.5°	3.7°	4.2°	6.5°	5.4°	5.1°
Ankle						
PRE						
Mean	130.3°	136.2°	134.2°	119.0°	119.2°	138.1°
SD	19.2°	6.3°	6.4°	13.6°	17.8°	87.1°
POST						
Mean	141.1°	140.5°	134.5°	125.6°	120.3°	133.2°
SD	5.0°	5.9°	6.4°	16.1°	13.7°	45.7°

Note: PRE: prepubescents; POST: postpubescents; DJL: drop jump lateral; DJV: drop jump vertical; DJS: drop jump static; SJL: stride jump lateral; SJV: stride jump vertical; SJS: stride jump static.

Table 3-3. Time to maximum knee flexion (ms) during the different jump landing sequences.

	DJL	DJV	DJS	SJL	SJV	SJS
PRE						
Mean	216	234	136	299	151	180
SD	20	66	24	81	25	87
POST						
Mean	249	211	215	283	234	244
SD	49	40	70	54	64	65

The range of motion of a lower extremity joint was measured as the change in angular orientation from the instant of touch down until the instant of maximum knee flexion. The mixed design analyses indicated significant main effects for jump type ($F(1,30) = 16.431$, $p < 0.001$), landing sequence ($F (2,60) = 20.65$, $p < 0.001$), and maturation ($F (1,30) = 7.739$, $p = 0.009$) in regards to the range of motion at the hip. Range of motion values for the hip, knee, and ankle joints during the six different jump-landing sequences can be found in Table 3-4. A greater hip flexion was observed in the postpubescents ($p = 0.009$) and during the performance of the drop jumps ($p < 0.001$). In regards to landing sequence, the lateral landings produced significantly more hip flexion than the vertical and static landings ($p < 0.001$). No significant interactions were identified for the range of motion of the hip. A significant Jump type x Landing sequence interaction was observed for knee range of motion ($F(2,60) = 5.778$, $p = 0.023$). An analysis of the ankle joint revealed significantly greater joint excursion at the ankle during the drop jumps compared to the stride jumps ($F(1,30) = 83.1$, $p < 0.001$). However, the mixed design analyses yielded no significant two or three way interactions, nor any main effects for landing sequence or maturation.

Kinetics

The typical time-history curve of the vertical GRF during a drop jump demonstrated two distinctive maximums with a first peak (F1) related to the toe contact and a second peak (F2) associated with heel contact (Figure 3-4). The vertical force increased sharply from the instant of foot contact and reached F1 in 0.012 s, 0.017 s, and 0.013 s in the DJL, DJV, and DJS conditions, respectively. The time to the F1 peak demonstrated insignificant Maturation x Landing sequence interactions and insignificant

Table 3-4. Mean range of motion in degrees of the lower extremity joints from the instant of touchdown until the time of maximum knee flexion.

	DJL	DJV	DJS	SJL	SJV	SJS
Hip						
PRE						
Mean	25.5°	21.6°	19.0°	18.1°	13.4°	11.9°
SD	8.8°	7.7°	11.1°	14.7°	8.4°	7.8°
POST						
Mean	32.8°	24.9°	23.8°	29.6°	19.1°	22.3°
SD	10.7°	10.3°	9.5°	11.4°	7.6°	11.3°
Knee						
PRE						
Mean	45.2°	44.3°	40.7°	42.9°	37.8°	33.8°
SD	5.4°	7.4°	7.7°	6.2°	7.7°	8.5°
POST						
Mean	48.4°	45.6°	43.2°	45.3°	38.3°	39.1°
SD	5.5°	4.8°	7.3°	6.1°	7.7°	5.8°
Ankle						
PRE						
Mean	38.3°	42.4°	40.1°	17.6°	19.2°	11.6°
SD	9.1°	7.0°	8.5°	14.1°	18.4°	12.1°
POST						
Mean	46.4°	46.0°	41.6°	12.2°	17.4°	19.0°
SD	5.5°	4.3°	9.4°	16.2°	12.9°	15.7°

Note: PRE: prepubescents; POST: postpubescents; DJL: drop jump lateral; DJV: drop jump vertical; DJS: drop jump static; SJL: stride jump lateral; SJV: stride jump vertical; SJS: stride jump static.

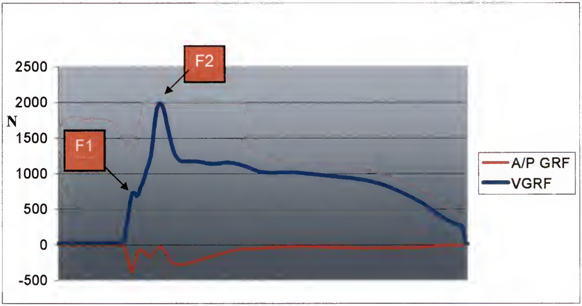


Figure 3-4. Ground reaction force time history curve showing location of the F1 peak and F2 peak vertical ground reaction force.

main effects for both Landing sequence and Maturation. The 2 x 2 x 3 ANOVA revealed significant main effects for jump type ($F(1,26) = 4.2$, $p=0.028$) and maturation ($F(1,26) = 5.69$, $p = 0.025$) for the time to the F2 peak. This time duration was significantly longer in postpubescents averaging 11.3 ms longer. The time to the F2 peak was also significantly longer for the drop jumps compared to the stride jumps. Landing sequence comparisons did not reveal a significant main effect for time to the F2 peak.

The magnitude of the F1 peak GRF was significantly greater in the prepubescents ($F(1,26) = 6.539$, $p = 0.019$). An analysis of the landing sequence yielded a significant main effect ($F(2,52) = 3.839$, $p = 0.030$) for the magnitude of the F1 peak. The static landing sequence produced a significantly larger F1 peak than the lateral and vertical conditions. Neither significant interactions, nor jump type main effects were observed. The 2 x 2 x 3 ANOVA results for magnitude of the F2 peak GRF demonstrated significant main effects for jump type ($F(1,26) = 134.03$, $p < 0.001$) and landing sequence ($F(2,52) = 3.87$, $p = 0.025$), and non-significant interactions. The F2 peak was significantly greater during the drop jumps. Post hoc analyses of the landing sequences indicated a significant difference between the lateral and static landing conditions with the static landing producing approximately 0.4 BW greater force. The maturation analysis did not detect a significant difference between the pre- and postpubescents. Tables 3-5 and 3-6 show the means of the F1 and F2 peaks for the pre and postpubescent participants during the six different jump-landing sequences.

The horizontal GRF placed a significant load on the participants and reached its maximum posterior shear at about 12 ms after floor contact. Mean peak anterior-posterior ground reaction forces are presented in Table 3-7. Analysis of the anterior-posterior GRF

Table 3-5. Mean peak F1 vertical GRF (BW) and time to peak F1 (ms).

		DJL		DJV		DJS	
Mat		F1	TF1	F1	TF1	F1	TF1
PRE							
	Mean	1.85	12	1.89	12	2.20	11
	SD	0.54	2	0.62	3	0.86	4
POST							
	Mean	1.39	12	1.41	12	1.45	11
	SD	0.62	3	0.44	2	0.30	3

Table 3-6. Mean peak F2 (F2) vertical GRF (BW) and time to peak F2 (TF2) (ms).

		DJL		DJV		DJS	
Mat		F2	TF2	F2	TF2	F2	TF2
PRE							
	Mean	4.00	39	4.37	41	4.27	42
	SD	1.07	12	1.40	7	0.96	10
POST							
	Mean	3.81	53	3.86	54	4.22	47
	SD	0.55	5	0.61	9	0.65	9

		SJL		SJV		SJS	
Mat		F2	TF2	F2	TF2	F2	TF2
PRE							
	Mean	2.17	31	2.65	27	2.45	27
	SD	0.53	19	1.52	17	0.71	16
POST							
	Mean	2.36	39	2.63	44	2.75	44
	SD	0.69	24	0.53	14	0.77	14

revealed a significant Maturation x Jump type x Landing sequence interaction ($F(2,78) = 4.302$, $p = 0.048$) (Figure 3-5).

Joint resultant forces provide important information about the internal forces within the musculoskeletal system. The mean and SD values of the hip, knee and ankle forces during the different jump-landing sequences are provided in Tables 3-8, 3-9, and 3-10. The analysis revealed a significant three-way interaction, Maturation x Jump type x Landing sequence, for peak knee anterior-posterior (A/P) force, ($F(2,52) = 4.606$, $p = 0.041$), a significant Maturation x Jump type two-way interaction for peak Knee P/D force, ($F(1,26) = 5.139$, $p = 0.032$) and peak ankle proximal-distal (P/D) force, ($F(1,26) = 7.248$, $p = 0.012$), as well as a significant Jump type x Landing sequence interaction for the peak ankle P/D force and the peak ankle medial-lateral (M/L) force. Graphical representations of these interactions are presented in Figures 3-6, 3-7, and 3-8. Significant differences were observed between the pre- and postpubescents in hip M/L force ($F(1,26) = 4.697, p = 0.040$), knee M/L force ($F(1,26) = 18.540$, $p < 0.0001$), ankle M/L force ($F(1,26) = 6.881$, $p = 0.014$) and knee A/P force ($F(1,26) = 9.731$, $p = 0.004$). The results indicated significant main effects for jump type in the following variables: peak Hip P/D force ($F(1,26)=145.196, p<0.001$), peak Hip A/P force ($F(1,26)=23.297, p<0.001$), peak Knee M/L force ($F(1,26)=11.058, p=0.003$), peak Ankle M/L force ($F(1,26)=15.74, p=0.001$), and peak Ankle A/P force ($F(1,26)=213.668, p<0.001$).

Significant main effects were observed among the three landing sequences for the following variables: hip P/D force ($F(2,52) = 12.56$, $p = 0.002$), knee P/D force ($F(2,52) = 14.656$, $p = 0.001$), knee M/L force ($F(2,52) = 10.473$, $p = 0.003$), and peak ankle A/P force ($F(2,52) = 12.602$, $p = 0.001$). Follow up tests revealed that the static landing

Table 3-7. Mean peak anterior-posterior ground reaction forces (BW) recorded during the different jump-landing sequences.

Mat		DJL	DJV	DJS	SJL	SJV	SJS
PRE							
	Mean	-0.84	-0.94	-0.92	-0.83	-0.94	-1.00
	SD	0.40	0.41	0.40	0.33	0.41	0.32
POST							
	Mean	-0.68	-0.66	-0.71	-0.74	-0.82	-1.02
	SD	0.15	0.21	0.17	0.31	0.27	0.29

Note: Negative values indicate posterior directed forces

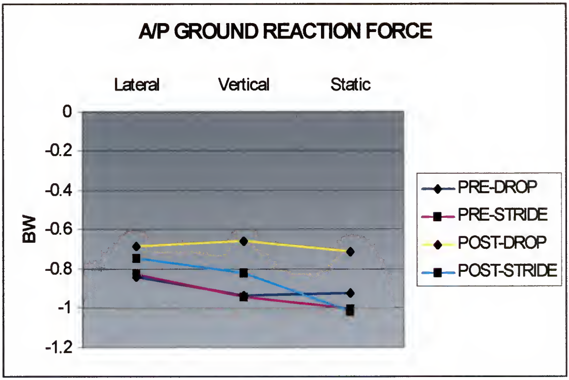


Figure 3-5. Graphical representation of the three-way interaction Maturation x Jump type x Landing sequence for the anterior-posterior ground reaction forces.

Table 3-8. Mean peak hip joint forces (N/kg) recorded during the different jump-landing sequences.

		DJL			DJV			DJS		
Mat		P/D	M/L	A/P	P/D	M/L	A/P	P/D	M/L	A/P
PRE										
	Mean	-37.2	3.9	-15.8	-37.0	2.0	-15.7	-38.7	0.8	-15.3
	SD	8.0	6.1	10.2	10.4	5.2	10.5	8.8	4.5	11.2
POST										
	Mean	-34.6	-1.5	-8.7	-32.5	-1.3	-6.1	-37.8	-1.5	-7.01
	SD	8.8	8.0	15.6	6.2	6.2	12.4	6.7	5.2	14.0

		SJL			SJV			SJS		
Mat		P/D	M/L	A/P	P/D	M/L	A/P	P/D	M/L	A/P
PRE										
	Mean	-20.8	3.8	-9.4	-20.3	3.5	-10.2	-23.8	3.0	-10.1
	SD	6.6	4.5	7.0	4.8	3.6	7.2	6.8	4.2	8.7
POST										
	Mean	-21.3	0.4	-4.2	-21.5	-1.0	-4.7	-25.2	-0.4	-5.4
	SD	5.4	4.7	10.3	6.7	5.2	11.2	6.3	4.3	10.9

Note: P/D: proximal-distal, negative values are distal directed forces.
M/L: medial-lateral, negative values are lateral directed forces.
A/P: anterior-posterior, negative values are posterior directed forces.

Table 3-9. Mean Peak knee joint forces (N/kg) recorded during the different jump-landing sequences.

		DJL			DJV			DJS		
Mat		P/D	M/L	A/P	P/D	M/L	A/P	P/D	M/L	A/P
PRE										
	Mean	44.4	-5.4	-9.3	43.9	-3.1	-10.0	45.3	-2.2	-8.8
	SD	8.3	5.6	2.3	11.4	5.0	2.3	9.3	4.3	3.7
POST										
	Mean	38.3	2.4	-11.2	38.0	3.0	-11.6	43.2	4.7	-11.4
	SD	5.7	5.4	2.3	7.2	5.8	2.3	7.2	2.3	2.1

		SJL			SJV			SJS		
Mat		P/D	M/L	A/P	P/D	M/L	A/P	P/D	M/L	A/P
PRE										
	Mean	24.8	-5.2	-1.4	23.9	-4.3	-3.2	27.6	-4.3	-3.7
	SD	6.9	3.8	7.0	4.7	3.3	6.2	7.7	3.7	7.2
POST										
	Mean	25.3	0.6	-9.5	25.0	1.6	-9.2	29.3	1.89	-7.6
	SD	6.8	4.8	2.1	8.4	5.4	4.6	7.4	4.3	5.4

Note: P/D: proximal-distal, negative values are distal directed forces.
M/L: medial-lateral, negative values are lateral directed forces.
A/P: anterior-posterior, negative values are posterior directed forces.

Table 3-10. Mean peak ankle joint forces (N/kg) recorded during the different jump-landing sequences.

		DJL			DJV			DJS		
Mat		P/D	M/L	A/P	P/D	M/L	A/P	P/D	M/L	A/P
PRE										
	Mean	-14.2	-5.4	-41.9	-15.2	-6.2	-41.4	-15.4	-6.0	-42.6
	SD	6.2	2.0	7.8	6.3	2.3	10.7	5.8	1.6	8.9
POST										
	Mean	-12.9	-2.2	-35.4	-12.9	-3.3	-35.2	14.3	-3.1	-39.9
	SD	2.5	3.1	5.4	2.9	3.2	6.8	2.7	3.4	6.9

		SJL			SJV			SJS		
Mat		P/D	M/L	A/P	P/D	M/L	A/P	P/D	M/L	A/P
PRE										
	Mean	-10.2	-1.4	-22.6	-10.7	-5.2	-21.8	-13.9	-4.3	-24.7
	SD	5.2	3.8	6.2	4.5	2.1	4.4	4.1	2.7	7.3
POST										
	Mean	-12.0	-0.3	-21.8	-12.8	-3.0	-23.6	-15.1	-2.9	-25.0
	SD	3.2	3.3	5.5	3.3	3.4	5.5	3.8	2.7	6.3

Note: P/D: proximal-distal, negative values are distal directed forces.
M/L: medial-lateral, negative values are lateral directed forces.
A/P: anterior-posterior, negative values are posterior directed forces.

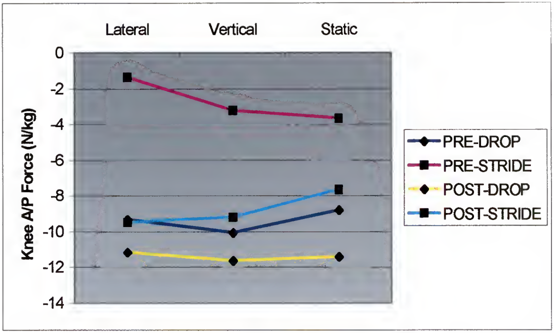


Figure 3-6. Graphical representation of the three-way interaction Maturation x Jump type x Landing sequence regarding knee anterior-posterior force.

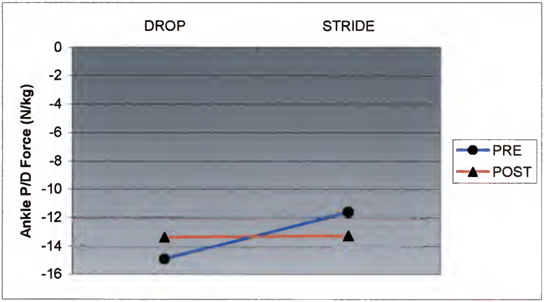


Figure 3-7. Graphical representation of the two-way interaction Maturation x Jump type regarding the proximal distal forces.

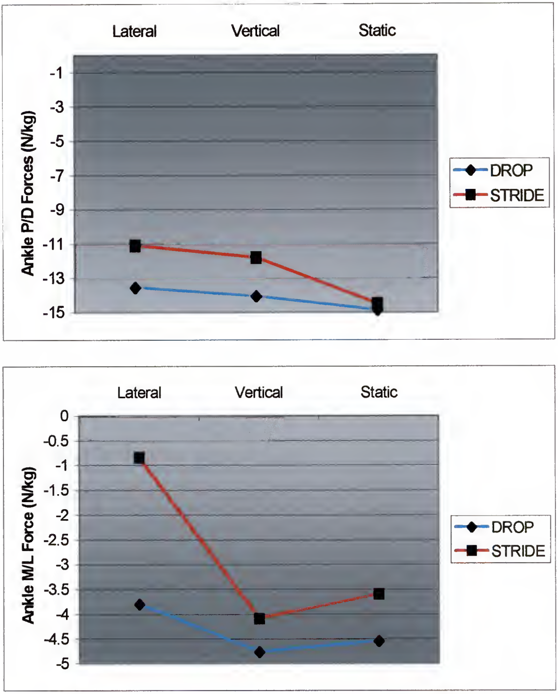


Figure 3-8. Graphical representation of the two-way interaction Jump type x Landing Sequence for the ankle joint forces.

produced significantly greater hip and knee P/D forces than those in either the lateral or vertical conditions ($p < 0.005$). The lateral landing sequence produced the greatest knee M/L forces ($p < 0.01$). The peak ankle A/P force was significantly greater in the static landing sequence ($p < 0.03$) compared to the lateral and vertical conditions.

Peak extensor moments and powers represent maximum efforts by certain muscle groups in energy absorption. Mean peak moments for the hip, knee, and ankle can be found in Tables 3-11, 3-12, and 3-13, respectively. The mixed model analysis revealed no three-way interaction. However, significant Maturation x Jump type interactions for the peak hip flexion-extension (F/E) moment ($F(1,26) = 5.268, p = 0.030$), knee F/E moment ($F(1,26) = 5.834$, $p = 0.023$) and the ankle F/E moment ($F(1,26) = 5.488, p = 0.027$) were observed. Graphical representation of these interactions can be found in Figure 3-9. For these extensor moments, the postpubescents had greater moments during the stride jumps. Conversely, during the drop jumps the prepubescents had greater moments of force. Thus, the prepubescents had a greater reduction in the extensor moments from drop to stride jumps. Significant Maturation x Landing sequence interactions were observed for the peak hip abduction-adduction (Ab/Ad) ($F(2,52) = 8.126$, $p = 0.008$), knee Ab/Ad ($F(2,52) = 7.624, p = 0.010$) and ankle Ab/Ad ($F(2,52) = 4.447, p = 0.045$) moments as well as the peak knee internal-external (Int/Ext) rotation moment ($F(2,52) = 6.620$, $p = 0.016$). Further, the analysis revealed a significant Jump type x Landing sequence interaction for the peak hip Int/Ext rotation moment ($F(2,52) = 5.519$, $p = 0.027$). Graphical representations of these interactions are presented in Figures 3-10 and 3-11.

Table 3-11. Mean peak hip joint moments (Nm/kg) recorded during the different jump-landing sequences.

		DJL			DJV			DJS		
Mat		F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot
PRE										
	Mean	-9.1	-0.4	-0.4	-12.3	-0.9	-0.6	-10. 8	-1.0	0.0
	SD	3.4	6.8	2.8	4.2	6.1	2.9	4.0	5.2	2.4
POST										
	Mean	-8.8	0.5	1.0	-9.1	-1.6	0.3	-10.6	-3.7	-0.2
	SD	2.7	7.1	2.1	10.7	6.9	2.3	3.7	7.7	2.7

		SJL			SJV			SJS		
Mat		F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/A d	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot
PRE										
	Mean	-3.0	-1.2	0.1	-4.3	-1.8	-1.4	-5.9	-1.5	-1.3
	SD	3.3	2.8	1.6	2.6	2.8	1.4	3.5	4.1	2.3
POST										
	Mean	-4.9	1.5	1.3	-5.3	-2.0	-0.7	-6.8	-1.3	-0.5
	SD	4.4	4.5	2.3	4.1	4.8	2.6	3.7	4.7	2.1

Note: F/E: flexion-extension, negative values are extension moments.
Ab/Ad: abduction-adduction, negative values are adduction moments.
In/Ex Rot: internal-external, negative values are external rotation moments.

Table 3-12. Mean peak knee joint moments (Nm/kg) recorded during the different jump-landing sequences.

		DJL			DJV			DJS		
Mat		F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot
PRE										
	Mean	-7.8	-1.1	1.4	-11.1	-1.3	1.9	-9.6	-1.7	1.8
	SD	3.2	6.8	1.6	3.8	6.2	1.9	3.7	5.1	1.3
POST										
	Mean	-7.3	1.0	0.3	-7.7	-1.3	1.1	-8.9	3.3	1.4
	SD	2.2	6.9	1.9	3.2	6.7	2.2	4.2	7.8	2.2

		SJL			SJV			SJS		
Mat		F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot
PRE										
	Mean	-1.6	-1.3	1.4	-3.3	-2.7	1.3	-5.2	-2.0	1.3
	SD	3.6	3.0	0.6	2.9	2.5	1.1	3.5	4.5	1.4
POST										
	Mean	-3.1	1.9	0.1	-4.3	-2.1	1.7	-5.9	-1.4	1.2
	SD	4.9	4.9	1.8	3.8	4.8	1.9	3.4	4.7	1.7

Note: F/E: flexion-extension, negative values are extension moments.
Ab/Ad: abduction-adduction, negative values are adduction moments.
In/Ex Rot: internal-external, negative values are external rotation moments.

Table 3-13. Mean peak ankle joint moments (Nm/kg) recorded during the different jump-landing sequences.

		DJL			DJV			DJS		
Mat		F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot
PRE										
	Mean	-8.0	-1.1	-3.6	-10.6	-1.3	-4.2	-9.4	-1.7	-4.6
	SD	3.8	6.8	6.0	4.5	6.2	6.3	3.6	5.1	4.6
POST										
	Mean	-6.7	1.0	0.1	-7.0	-1.3	-2.6	-8.1	3.3	-3.6
	SD	2.7	6.9	6.4	3.1	6.7	6.6	4.4	7.8	7.8

		SJL			SJV			SJS		
Mat		F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot
PRE										
	Mean	-1.2	-1.3	-1.5	-3.2	-2.7	-3.06	-4.8	-2.0	-3.6
	SD	3.7	3.0	2.5	3.1	2.5	2.3	3.3	4.5	4.3
POST										
	Mean	-2.4	1.9	1.2	3.9	-2.1	-2.2	-4.7	-1.4	-2.2
	SD	4.2	4.8	4.4	2.7	4.8	5.0	4.1	4.7	4.4

Note: F/E: flexion-extension, negative values are plantarflexion moments.
Ab/Ad: abduction-adduction, negative values are adduction moments.
In/Ex Rot: internal-external, negative values are external rotation moments.

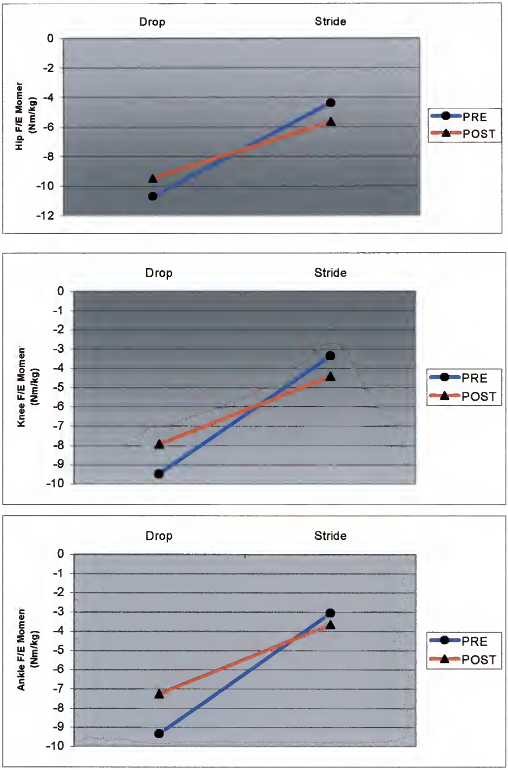


Figure 3-9. Graphical representation of the two-way Maturation x Jump type interaction for the flexion-extension moments of the hip, knee, and ankle.

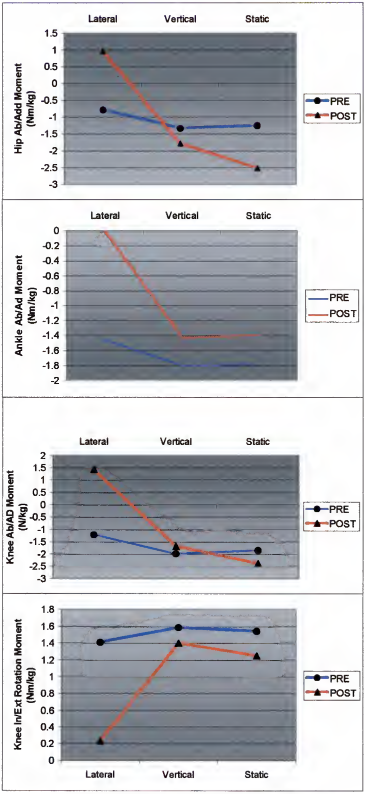


Figure 3-10. Graphical representation of the Maturation x Landing sequence interaction for abduction-adduction and internal-external rotation moments.

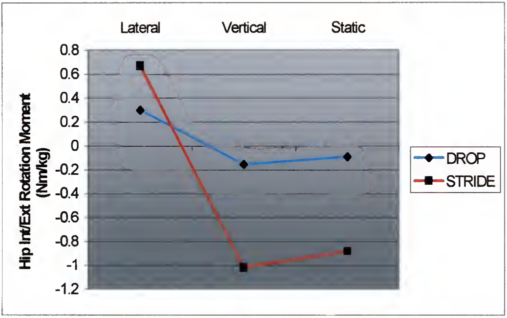


Figure 3-11. Graphical representation of the two-way interaction Jump type x Landing sequence for hip internal-external moments.

Peak powers for the knee and ankle observed during the jump-landings can be found in Tables 3-14 and 3-15, respectively. Analyses of the peak powers revealed a significant three way interaction, Maturation x Jump type x Landing sequence, for both peak Knee F/E power ($F(2,52) = 3.893$, $p = 0.027$) and Ankle F/E powers ($F(2,52) = 3.348$, $p = 0.043$). Graphical representation of these three-way interactions is presented in Figure 3-12. A significant Maturation x Jump type two way interaction was observed for both the peak Knee Int/Ext rotation power ($F(1,26) = 7.963$, $p = 0.009$) and Ankle Int/Ext rotation power ($F(1,26) = 10.982$, $p = 0.003$) which can be observed graphically in Figure 3-13.

Discussion

The knee joint, located between the two longest bones in the body, is particularly susceptible to injury during a jump-landing sequence (Dufek & Bates, 1990). Indeed, the jump-landing sequence is the most frequent mechanism of injury in the sports of basketball and volleyball (Briner & Kacmar, 1997; Gerberich et al., 1987; Gray et al., 1985; Solgard et al., 1995). Epidemiological evidence suggests that female participants are particularly susceptible to injuries during this task and that the incidence of knee injuries in female athletes increases as the individual undergoes the maturation process. Despite this information, little is known about the landing mechanics of female athletes and the potential influence the maturation process has on the performance of the jump-landing sequence. Thus, the purpose of this study was to identify and compare ground reaction forces, joint positions, forces, moments, and muscle powers in the lower extremity during different jump and landing combinations in pre- and postpubescent females.

Table 3-14. Mean peak knee joint power (W/kg) recorded during the different jump-landing sequences.

		DJL			DJV			DJS		
Mat		F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/ Ad	In/ Ex Rot	F/E	Ab/ Ad	In/Ex Rot
PRE										
	Mean	-52.1	-1.50	4.62	-82.51	-0.64	6.32	-67.57	0.10	6.10
	SD	22.66	19.99	6.00	34.33	14.49	8.33	36.34	13.19	4.99
POST										
	Mean	-52.9	-4.93	-1.30	-54.87	-2.89	0.79	-62.46	1.11	1.59
	SD	25.43	14.19	6.52	28.97	12.30	6.98	30.94	12.89	5.29

		SJL			SJV			SJS		
Mat		F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/Ad	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot
PRE										
	Mean	-11.3	-0.18	5.38	-15.55	4.04	4.19	-24.51	2.80	4.14
	SD	16.68	5.00	3.37	16.22	5.93	6.22	15.52	6.74	7.55
POST										
	Mean	-17.7	-0.72	1.58	-26.94	-1.79	5.25	-28.76	-0.48	2.84
	SD	22.45	6.03	3.35	26.47	11.20	4.42	24.36	7.23	5.01

Note: F/E: flexion-extension, negative values are extension power.
Ab/Ad: abduction-adduction, negative values are adduction power.
In/Ex Rot: internal-external, negative values are internal rotation power.

Table 3-15. Mean peak ankle joint power (W/kg) recorded during the different jump-landing sequences.

		DJL			DJV			DJS		
Mat		F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot	F/E	Ab/ Ad	In/Ex Rot
PRE										
	Mean	73.12	-4.62	-12.28	103.30	-6.25	-13.93	81.5	-6.67	-12.56
	SD	42.0	14.86	17.02	48.22	19.20	20.40	42.2	10.19	12.47
POST										
	Mean	69.04	-0.07	2.01	67.29	-6.01	-.21	72.2	-6.03	-.45
	SD	28.96	12.89	9.84	33.99	13.27	12.04	28.6	15.28	15.82

		SJL			SJV			SJS		
Mat		F/E	Ab/Ad	In/Ex Rot	F/E	Ab/Ad	In/Ex Rot	F/E	Ab/Ad	In/Ex Rot
PRE										
	Mean	1.41	-4.24	2.27	-.26	-7.86	3.85	-12.5	-5.61	7.33
	SD	21.34	6.79	6.70	27.83	10.18	8.91	27.52	9.59	12.81
POST										
	Mean	13.25	2.84	-2.18	-.26	-3.85	-4.09	-12.5	-2.86	-1.65
	SD	31.00	9.94	5.80	27.83	14.24	13.67	27.52	10.87	12.02

Note: F/E: flexion-extension, negative values are extension power.
Ab/Ad: abduction-adduction, negative values are adduction power.
In/Ex Rot: internal-external, negative values are external rotation power.

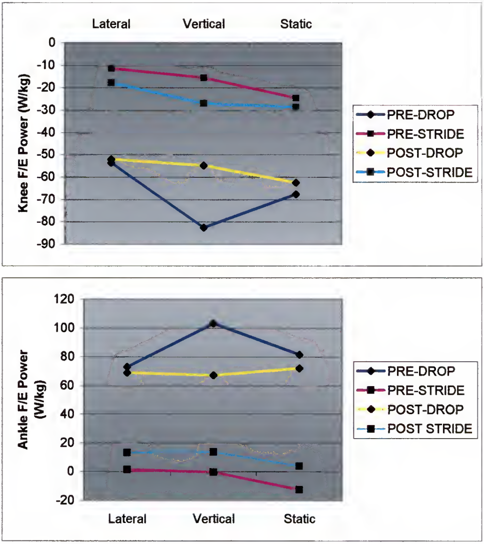
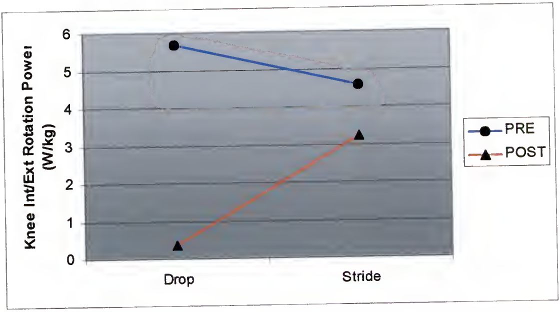


Figure 3-12. Graphical representation of the three-way Maturation x Jump type x Landing sequence interaction for extensor power of the knee and ankle.



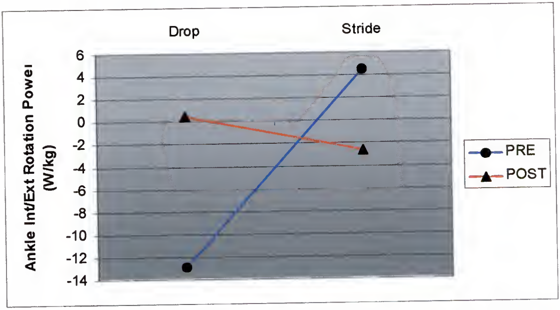


Figure 3-13. Graphical representation of the two-way Maturation x Jump type interaction for the knee and ankle internal-external rotation powers.

Joint Kinematics:

The joint position results suggest selective adjustments in the descent phase such that the angular positions of the lower extremity joints were different in the two maturation groups at the instance of contact. This finding may indicate functionally different landing strategies utilized by the pre- and postpubescents female athletes. Prepubescents landed with a more flexed position and flexed less after making contact with the ground. Conversely, the postpubescents were more erect at the instance of touchdown and they used a greater range of motion to dissipate the impact forces. Hip, knee, and ankle angular displacements during the landing phase were significantly larger in the drop jumps compared with those in the stride jumps. These findings are countered by the results of Kovacs et al. (1999), who observed a greater joint range of motion in heel-toe landings compared to fore-foot landings. However, this discrepancy can be explained by the fact that participants performed the two different techniques when landing from a drop jump whereas, in the present study the heel-toe landing was a result of a horizontal stride jump. The average angular displacements of the hip, knee, and ankle during the impact phase were similar to the corresponding values reported by Kovacs et al. (1999) and Zhang, Bates, Dufek (2000).

Results in the present study indicate that the goal of the movement after initial contact has implications on the lower extremity joint motion. The ballistic activities, jumping vertical or lateral after contact, required prolongation of the flexion phase. This increased flexion may have allowed for greater stretching of the extensor mechanism which could have subsequently been used to propel the individual in the vertical or lateral direction.

<u>Kinetics</u>

The observed landing vertical GRF curves were similar to those presented previously in studies in which subjects jumped up from the floor (Gross 1988;Valiant & Cavanagh, 1988) and/or stepped off a raised platform (Devita & Skelly, 1992). The temporal characteristics of the vertical GRF curves indicated that the major impact phase ended after approximately 100 ms. Two vertical force peaks were observed at approximately 12 and 40 ms during the impact phase. These values are similar to the average times from contact to F1 and F2 of 9.6 and 44.2 ms reported by Zhang, Bates, Dufek (2000). The increased knee flexion and lower vertical GRF observed in the postpubescent athletes in this study are in agreement with previously reported values for soft landing techniques (Devita & Skelly, 1992). The peak vertical GRF magnitudes observed during the drop jumps (3.3 BW) were slightly less than those previously reported. Prapavessis and McNair (1999) reported an overall mean peak vertical GRF of 4.5 BW, while Dufek and Bates (1990) reported a mean peak force of 3.85 BW. This difference is likely due to differences in drop landing height. In the present investigation, the landing height was scaled to match the maximum vertical jump height of each participant while in previous investigations participants landed from heights ranging from 0.3 to 0.5 m. The horizontal GRF also placed a substantial load on the participants. In the present investigation, the peak horizontal GRF averaged 0.89 BW during the stride jumps while Simpson and Kanter (1997) reported an average peak horizontal ground reaction force of 0.82 BW during travelling jumps in dancers. The drop jumps exhibited an average peak horizontal GRF of 0.79 BW, which is comparable to values reported previously (DeVita & Skelly, 1992).

Several researchers have suggested that impact forces at landing occur too rapidly to be modified by a reaction response from the neuromuscular system (Denoth, 1985; Devita & Skelly, 1992; Lees, 1991). Rather, modifying the activity of the lower extremity before contacting the landing surface, which may include presetting of muscle tensions, is required to reduce the external impact forces. The results of the present study support the hypothesis that the positioning of the lower extremity joints prior to impact has a direct influence on the kinetics of the landing performance. The more flexed landing position of the prepubescents coupled with a more stiff landing technique resulted in a significantly greater F1 peak vertical GRF and a faster time to the F2 peak vertical GRF. The more flexed position at landing, however, may be a protective strategy by which increasing the moment arm of the hamstrings (due to greater knee flexion) results in a reduction of ACL loading. Support for this hypothesis is found in the reduced knee anterior-posterior forces observed in the prepubescent athletes. However, the increased angular displacements of the hip, knee and ankle coupled with the greater duration of knee flexion observed in the postpubescents resulted in a reduction in the vertical GRF. It appears that the kinematic and ground reaction force differences between the two groups may be related to their differences in muscle activation patterns, which warrant future research.

The influence of landing sequence was investigated to determine its influence on the kinematics of the lower extremity as the GRF were dissipated. The landing sequences were chosen to mimic the types of landings identified formerly during competitive volleyball matches (Tillman, Hass, Brunt, & Miller, 2001). The results observed here indicate that the landing sequences did not influence the shape of the GRF curves or the timings of the peak magnitudes but did influence the magnitude of the vertical GRF. The

landing sequence also influenced the range of motion of the lower joints and the timing of maximum knee flexion.

Limited efforts have been made to estimate the loads acting on specific joints during landing movements. Panzer (1987) examined the dynamic loading of the lower extremity joints during the landing phase of a double somersault. He reported that the average maximum knee joint resultant force in the longitudinal direction was 2,106 N. In the present investigation, single leg drop jump landings produced longitudinal knee joint forces averaging 1,889 N. Single legged stride jump landings produced knee joint forces averaging 1,189 N. Simpson and Kanter (1997) reported an average axial knee joint force of 20.38 N/kg during traveling jumps in dancers. Similarly, axial knee joint forces ranging from 23.91 to 29.31 N/kg were produced during the stride jumps in the present study. However, ankle joint axial forces reported in the Simpson and Kanter study were 1.7 times greater than those observed during the stride jumps in the present study. Shear force loadings have been implicated in both repetitive and acute injuries to the lower extremity joints (Simpson & Pettit, 1997). Knee and ankle anterior-posterior forces observed were 0.5 and 2 times the corresponding values reported by Simpson and Petit. The anterior-posterior force at the knee in the present study was directed such that the ACL was the primary ligamentous restraint. Across the six different jump-landing sequences, knee anterior-posterior forces in the postpubescents were greater than those observed in the prepubescents which may be indicative of the greater incidence of knee injury observed after the maturation process. Interestingly, the significant interactions indicated that the difference in knee anterior-posterior force in these two groups is greatest in the stride jumps.

Knowledge of the moments generated by the lower extremity muscles acting at the hip, knee, and ankle provide information regarding the control of the segment motion during a landing. The goal of a successful landing is to resist the collapse of the lower extremity by applying extensor moments of force to reduce the body's downward velocity to zero without injury (DeVita & Skelly, 1992). The extension moments of the hip, knee, and the plantarflexion moment at the ankle observed in this study were greater in magnitude than those reported previously. Simpson and Kanter (1997) reported peak knee extension and peak ankle plantarflexion moments of 3.33 and 1.6 Nm/kg, respectively, during traveling jumps in dancers. In the present study, knee and ankle moments averaged 3.89 and 3.35 Nm/kg, respectively, for the stride jumps. McNitt-Gray (1993) observed peak ankle, knee, and hip moments of 5.1, 4.57, and 12.09 Nm/kg, respectively, during drop landings. These values are considered similar to the 8.28, 8.71, and 10.1 Nm/kg, observed in the present investigation when accounting for the fact that the participants performed one-legged landings in the present investigation. The significance of the hip, knee, and ankle were greater in the drop jumps as indicated by the greater moments and powers compared to values produced during the stride jumps. Examination of the relative increases in peak extensor moments suggests the ankle plantarflexor and knee extensor muscles experience relatively larger demands than the hip when landing from a drop jump. Devita and Skelly (1992) reported highest mean torque at the hip joint, as did Kovacs et al. (1999) who observed greater peak torque at the hip followed by the knee and ankle. Similarly, peak moments were presently observed to decrease from the hip to the knee to the ankle. The significant Jump type x Maturation interactions for the extensor moments of the lower extremity joints indicate

that the two different jump types place different mechanical demands on the two population groups. For example, the magnitude of the knee extension moment during the stride jumps was approximately 30% of the corresponding magnitude observed during the drop jump in the prepubescents. In the postpubescents, the knee extension moment observed during the stride jumps was nearly 45% of the observed magnitude in the drop. Further, the magnitudes of the extension moments for all three joints in the prepubescents were larger than the corresponding values in the postpubescents in the drop jump. However, this trend reversed in the stride jumps where all three extension moments were greater in magnitude in the postpubescent group.

Analyses of the net joint moments and net joint powers of the lower extremity joints provide insight into the selective process by which participants control joint motion and attenuate the impact loads of landing (McNitt-Gray, 1993). These extensor moments observed primarily worked eccentrically to absorb the kinetic energy of the landing task. Indeed, the peak muscle powers for all the lower extremity joints highlighted the eccentric demands of the landing activity. Bobert, Huijing, and van Ingen Schenau (1987) reported that the highest mean power was produced by the ankle plantarflexors followed by the hip and knee extensors when using a forefoot landing strategy. The results of the present study support this trend as the knee extension and ankle plantar flexion powers averaged 62 W/kg and 77.75 W/kg for the drop jumps, respectively. In contrast, Kovacs et al. (1999) reported that the knee extensors had the highest power during heel-toe landings followed by the hip extensors and ankle plantarflexors. On average, the knee extension power was 13W/kg greater than the ankle plantarflexion power during the stride jumps in the present study. These peak values are in agreement with those reported

by McNitt-Gray (1993) and Devita and Skelly (1992) when one considers the differences in the activities performed in these studies. The results of this study are also in accord with the previous literature indicating that the significance of each joint's contribution to total power changes as a function of the landing technique and the magnitude of the forces applied to the body.

Conclusions

The jump-landing sequence is an integral part of many of our most popular sports. Consequently, this activity has been studied for many years. However, the research has focused primarily on male participants performing laboratory based jump-landing tasks. The present investigation was a first attempt to investigate the kinetics of landing in two different populations of female athletes performing more sports specific jump and landing tasks. The results of this investigation indicated that the prepubescent athletes, as a group, landed in a slightly more flexed position, used less range of motion, a shorter landing phase time, similar extensor moments and greater eccentric muscle power than the postpubescent athletes when performing the different jump-landing combinations. The significant maturation by jump type interactions observed for various dependent variables indicated that the two groups respond differently depending on the nature of the jump-landing activity. Analyses of the three different landing sequences indicated that these tasks did not have a significant influence on the sagittal plane motions and actions of the lower extremity during the period from touchdown to maximum knee flexion. However, the landing sequence tended to influence the secondary planes of motion more dramatically.

In conclusion, the primary findings of this investigation suggest functionally different movement strategies exist in these two populations. The possible relationship between these differences and the increased susceptibility to injury warrants further research. However, training and rehabilitation specialist should consider these differences when designing conditioning and rehabilitation programs for these athletes. For example, technique and muscular training should be specialized to the particular jump task that the female athlete will perform as well as tailored to the individual themselves.

CHAPTER 4
COORDINATIVE ACTIONS OF THE LOWER EXTREMITY DURING LOCOMOTION AND LANDINGS.

The foot and lower extremity must dissipate extremely high ground reaction forces when landing from a jump. Vertical ground reaction forces (GRF) as high as 2–7 times body weight (BW) have been reported during drop jumps from platforms ranging in height from 20.3 cm to 100 cm (DeMont, Lephart, Giraldo, Swanik, & Fu, 1999; Dufek et al., 1989; Dufek et al., 1990; Mizrahi & Susak, 1982; Zatsiorski & Priluski, 1987). During more specific sporting maneuvers even greater ground reaction forces have been observed. For example, Stacoff et al. (1988) observed GRF ranging up to 9 BW during landings following a spike for female volleyball players. Further, Miller and Nissinen (1987) reported an average peak vertical GRF of 13.6 BW for nine male gymnasts during landing from a running forward somersault. The ability of the musculoskeletal system to attenuate these large impact forces is critical to injury prevention.

Gray et al. (1985) reported that 58% of all injured basketball players were injured while landing from a jump. Specifically, knee joint injuries accounted for 72% of these injuries. The jump-landing sequence is also the most common source of injury in volleyball with the majority (90%) of injuries occurring in the lower extremity with the knee joint being particularly vulnerable (Briner & Kacmar, 1997). Gerberich et al. (1987) reported that knee injuries accounted for 59% of lower extremity injuries. Injuries

to the knee joint are especially important because they are associated with more lost time from sports participation than other orthopedic injuries (Solgård et al., 1995). Perhaps the most serious knee injury resulting from landing is a rupture of the anterior cruciate ligament (ACL). Kirkendall and Garrett (2000) reported that the majority of non-contact ACL injuries occurred during landing from a jump or during cutting maneuvers. They also observed that when an injury occurred, the knee was near full extension (30° to full extension), internally rotated, and in valgus. Though different mechanisms of ACL injury have been proposed, tibiofemoral rotation appears to be a common link (Hess et al., 1994; Jarvinen, et al., 1994; Noyes, Matthews, Mooar, & Grood, 1983a; Noyes, Mooar, Matthews, & Butler, 1983b).

During ballistic activities such as running and landing from a jump, the actions of ankle dorsiflexion, knee flexion, and subtalar joint (STJ) pronation are associated with attenuation of the impulse shock load (Stergiou et al., 1999). Recently this coordinative action between pronation of the STJ and knee motion has received considerable attention. Specifically, Sterigiou et al. investigated the relationship between pronation and knee flexion. During knee flexion, the tibia rotates internally due to the greater length of the medial femoral condyle compared to the lateral condyle (Norkin & Levangie, 1992). Internal tibial rotation is also imparted by pronation occurring at the STJ. During the landing phase of a jump and during the early stance of walking and running, the STJ pronates and the knee joint flexes to allow for the impact forces to be absorbed. Both of these compensatory movements cause internal tibial rotation. Stergiou et al. suggests that asynchrony in the timing between the two joint actions may lead to an antagonistic relationship and increased susceptibility for knee injury. Excessive pronation of the foot

has also been implicated as being contributory to increased rotary stress at the knee and hip. Several researchers have documented the close relationship between STJ pronation and internal tibial rotation during walking and running. Cornwall and McPoil (1995) reported a +.95 correlation between pronation and tibial rotation during walking. Moreover, Nigg and colleagues (1993) observed a direct coupling (r = .99 correlation) between pronation and tibial rotation during running. To date, few studies have assessed the relationship between foot pronation and tibial and femoral rotation during dynamic activities or how these relationships may change based on the activity. Reischl and colleagues (1999) investigated the relationship between whole foot pronation and transverse plane rotation of the tibia and femur in walking. They reported that the magnitude and timing of peak pronation were not predictive of the magnitudes and timings of tibial and femoral rotation. Conversely, McClay and Manal (1997) found significant relationships between rearfoot eversion and both knee internal rotation and tibial internal rotation while investigating coupling parameters in runners. Recently, Stacoff et al. (2000) investigated the coupling coefficient (defined as the ratio of total internal tibial rotation over total eversion) between calcaneal inversion and tibial rotation during barefoot and shod running using intracortical bone pins. They reported coupling coefficients of positive .66 and .64 for barefoot and shod running, respectively. The equivocal observations between these studies suggest the relationship between foot motion and tibial and femoral rotations during locomotion remains unclear.

Injuries to the knee joint during landing from a jump are well documented. Some injuries may occur as the tibiofemoral joint accepts stress during landing activities because of the transmission of GRF that are nearly 5-6 times those seen in normal

walking (Winter & Bishop, 1992). However, these forces imparted on the lower extremity joints may be influenced by the landing strategy. For example, Kovacs et al. (1999) found that the peak GRF associated with a heel-toe landing is up to 3.4 times higher and occurs much more rapidly than the corresponding values found in a fore-foot landing. Further, Kovacs et al. (1999) suggested that the high rate of force development in heel-toe landing resulted in greater requirement for energy absorption by the soft tissues in the lower extremity. Presumably, asynchrony in the shock absorbing motions of pronation and knee flexion may lead to an even greater susceptibility for soft tissue injury around the knee joint. Interestingly, while many athletes perform vertical and horizontal jumps that require both a fore-foot and a heel-toe landing during practice and competition, a critical evaluation of the synchrony of the lower extremity joints has not been performed. Furthermore, the influence of manipulating the activity on joint coupling has not been deciphered. The relationships among rearfoot motion, whole foot eversion, and lower extremity rotation needs to be established to better understand the influence that foot mechanics have on the kinematics of the lower extremity. Therefore, the purpose of this study was to investigate the coupling parameters among rearfoot motion, whole foot eversion, knee flexion, tibial rotation, and knee internal/external rotation during locomotive and landing tasks. Specifically, the influences the force dissipating requirements of the task have on these inter- and intra-joint relationships were studied.

Methods

Participants

Twenty recreationally active women ranging in age from 18-30 years participated in this study. Participants regularly performed jump-landing movements as components

of their exercise and sports activities and were free from any orthopedic or neurologic conditions that influence lower extremity mechanics. Before participation, each subject read and signed a written inform consent statement approved by the Institutional Review Board.

Instrumentation

To investigate the relationship between foot and knee motion during locomotion and landings, participants were asked to walk, jog, and perform both a one legged vertical jump and a "hop test for distance" (Tegner, Lysholm, Lysholm, & Gillquist, 1986). Locomotive and landing kinematic characteristics were evaluated using two high-speed video cameras (SR 500 Kodak Motion Corder Analyzer; Eastman Kodak Corporation, San Diego, CA) providing frontal and sagittal views at 250 Hz (Figure 4-1). A Bertec force platform (Bertec Corporation, Columbus, Ohio) embedded into a level platform served as the landing area and a trigger for video acquisition. Video sampling was initiated 20 ms prior to initial contact and continued for 300 ms following first contact with the plate for the hopping and jumping trials. During the walking and jogging trials, video sampling began 20 ms prior to heel contact and continued until the stance foot was no longer in contact with the force platform. Video recordings were analyzed using a Peak Motus motion analysis system (Peak Performance Technologies, Englewood, CO). Anthropometric and structural alignment measurements were made using an anthropometer (Seritex Inc., New York, NY) and a plastic goniometer (Baseline Diagnostic Measuring Instruments). The maximal horizontal hop distance was measured using a measuring tape.

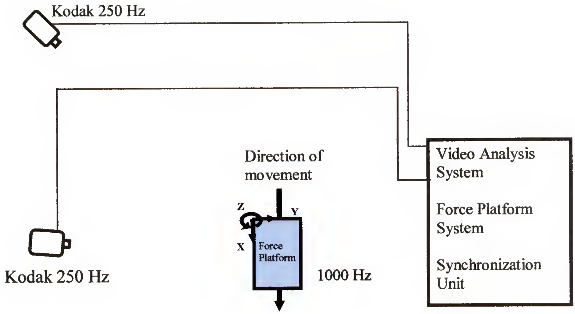


Figure 4-1. Overhead view of the testing environment showing camera placement relative to the force platform.

Procedures

After reading and signing an informed consent agreement, participants were fitted with black tight-fitting shorts and were asked to remove their shoes and socks. At this point, a series of anthropometric measures were made including body mass, girths of the calf and thigh, widths of the knee, ankle, and metatarsal head, femoral length, tibial length, and malleolar height and length of the foot on the dominant lower extremity. Goniometric measurements of the foot that were measured included: position of the rearfoot and forefoot when the subtalar joint was held in the neutral orientation and the position of the rearfoot during weight-bearing stance. The navicular drop test was also utilized as a clinical measure of pronation. Measurement of navicular drop was accomplished by the method described by Loudin et al. (1996). To avoid inter-rater variability concerns, the same investigator made all of the anthropometric and goniometric measurements.

Upon the completion of the alignment measures, participants warmed-up by walking for five minutes on a motorized treadmill. Following the initial general warm-up, the participants performed five practice trials of both the hop test and maximal vertical jump to familiarize themselves with the tasks. The toe-to-heel horizontal displacement was measured for each of the five practice jumps for the hop condition. The average displacement was calculated and was used to determine the target horizontal displacement for the experimental session.

Reflective markers were placed over the proximal calcaneus, distal calcaneus, metatarsal head II, proximal tibia, distal tibia, lateral malleolus, mid shank, lateral knee, lateral thigh, greater trochanter, and ASIS of the participant's leg to allow for automatic

tracking of lower extremity segmental movements (Figure 4-2). Markers were placed in a manner similar to that described by Vaughn et al. (1999). With this orientation, the markers allowed for the anatomical coordinate systems to be embedded within the thigh, shank and foot segments which were used to track segment motion. Data collection began with each participant performing three self-paced walking trials followed by three self-paced jogging trials over an 8-m level walkway. Following the locomotive trials, participants performed the hop test or the vertical jump in a random order. Each condition was initiated by a verbal signal by the investigator and each participant performed three trials of each condition with the individual taking off and landing on their dominant leg. The hop test for distance trials were initiated from a fixed distance from the force plate (maximum hop distance), as the participant stood on the laboratory walkway with their nondominant leg held in front of the body. Participants began these trials with their arms akimbo and performed a maximal horizontal hop off of their dominant leg then landing with their dominant leg on the force platform. All participants were encouraged to land with their foot in the center of the force platform. One-legged vertical jumps were initiated with the participant standing in a balanced position (arms akimbo) next to the force platform with their contralateral non-weight bearing leg held with the knee bent approximately 90° and positioned next to the dominant stance limb. Participants performed a vertical jump with maximal effort and landed with their dominant limb on the force platform. Unsuccessful hop and drop landings due to loss of balance, touching the floor with the contralateral limb, or a short additional hop upon landing were immediately repeated. Subjects were allowed approximately 2 minutes between trials for each of the four activities.

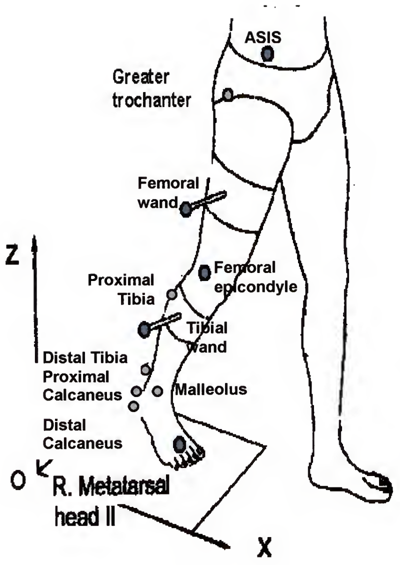


Figure 4-2. Marker placement on the test participant.

Data Reduction

Anthropometric and goniometric measurements for each participant were entered directly into an Excel spreadsheet. Each reflective marker was digitized and the coordinates were scaled and smoothed using a fourth order Butterworth filter with an optimal cut-off frequency determined by the Jackson Knee Point Method (Jackson, 1979) and a commercial software package (Peak Performance Technologies Inc., Englewood, CO). The angular kinematics of the knee joint about the flexion-extension and internal-external rotation axes were calculated with the distal segment referenced to the proximal segment as described elsewhere (Vaughn et al., 1999) with the exception that the greater trochanter marker was used to predict the location of the hip joint center. Tibial rotation and femoral rotation were calculated as the rotation of the proximal segment relative to the distal segment as described by Nigg et al. (1993). It has been suggested that this more accurately represents axial rotation of the tibia and femur in a closed chain situation and facilitates comparison among previous research (McClay & Manal, 1997). Rearfoot motion was calculated using the difference in the absolute angles of the leg and the calcaneus in the frontal plane (Figure 4-3). The magnitude of motion at the lower extremity joints were calculated as the peak range of motion during the time from touchdown to maximal knee flexion in the loading phase as described by McClay and Manal (1997) (Figure 4-4). Coupling coefficients, defined as the ratio of rearfoot motion to tibial rotation (McClay & Manal, 1997), the ratio of foot eversion to tibial rotation, the ratio of rearfoot motion to knee internal rotation, and the ratio of foot eversion to knee internal rotation were also determined.

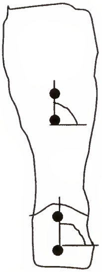


Figure 4-3. Calculation of the rearfoot angle. Rearfoot angle = $\theta_{\text{calcaneous}} - \theta_{\text{leg}}$

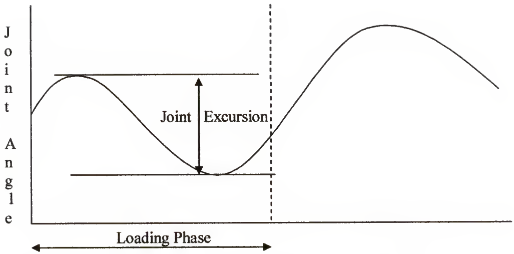


Figure 4-4. Determination of joint excursion during the loading phase.

Statistical Analyses

Descriptive statistics (Mean $\pm$ SD) for age, height, and weight were calculated. Measures of central tendency and variability were calculated for anthropometric and goniometric values, the magnitude and timing of rearfoot motion, foot eversion, knee flexion, tibial rotation and knee internal/external rotation during both experimental landing conditions. To assess the relationship between types of activity and lower extremity motions a one-way repeated measures MANOVA was performed on the coupling coefficients. The original level of significance for all tests was set at 0.05. Correlation analyses were performed to assess the relationship between inter-joint and intra-joint excursions for each of the four different dynamic activities. The following foot-knee excursion relationships were evaluated: (1) dorsiflexion and knee flexion, (2) whole foot eversion and knee flexion, (3) rearfoot motion and knee flexion, (4) whole foot eversion and tibial rotation, (5) rearfoot motion and tibial rotation, (6) whole foot eversion and knee internal rotation, and (7) rearfoot motion-knee internal rotation. The within foot relationships studied included whole foot eversion and rearfoot motion.

Results

Participant Characteristics

Twenty recreationally competitive female athletes (age: 21.5 $\pm$ 2.2 years; mass: 59.4 $\pm$ 5.9 kg; height: 166.4 $\pm$ 11.1 cm) participated in the study. These individuals regularly participated in activities requiring jumping and landing and were free from neuromuscular or orthopedic conditions that may have influenced landing performance. A summary of the static goniometric measurements of the participants can be found in Table 4-1.

Table 4-1. Characteristic information for the test participants.

Characteristic		Values
Weightbearing		
Rearfoot angle (valgus°)	Mean	7.1
	SD	2.9
Non-Weightbearing		
Rearfoot angle: (varus°)	Mean	2.8
	SD	2.5
Forefoot angle (varus°)	Mean	5.4
	SD	2.6
Navicular Drop (mm)	Mean	9.1
	SD	0.5

Table 4-2 presents the lower extremity joint excursions during the different dynamic activities. The results of the correlation analyses on inter- and intra-joint excursions are presented in Tables 4-3 and 4-4, respectively. In the vertical jump task, significant correlations were found between knee flexion and ankle dorsiflexion ($r = 0.45$, $p = 0.047$), between ankle dorsiflexion and foot eversion ($r = 0.47$, $p = 0.035$), and between knee internal rotation and femoral rotation ($r = 0.49$, $p = 0.028$). Several significant correlations were observed during the jogging trials. These significant excursion relationships include: knee flexion and foot eversion ($r = 0.53$, $p = 0.019$), ankle dorsiflexion and foot eversion ($r = 0.60$, $p = 0.005$), knee internal rotation and tibial internal rotation ($r = 0.45$, $p = 0.047$), knee internal rotation and femoral internal rotation ($r = 0.68$, $p = 0.001$), tibial internal rotation and femoral internal rotation ($r = 0.55$, $p = 0.012$), and femoral internal rotation and rearfoot eversion ($r = 0.52$, $p = 0.019$).

During the hopping task, several significant intra-joint and inter-joint relationships were observed. Rearfoot eversion was significantly correlated with ankle dorsiflexion ($r = 0.60$, $p = 0.005$), and foot eversion ($r = 0.72$, $p < 0.001$). A significant relationship was also found between femoral internal rotation and knee internal rotation ($r = 0.54$, $p = 0.014$).

Rearfoot eversion was significantly correlated with knee and ankle motion during walking. Specifically, rearfoot eversion was significantly correlated with knee flexion ($r = 0.46$, $p = 0.04$), ankle dorsiflexion ($r = 0.79$, $p < 0.001$), foot eversion ($r = 0.58$, $p = 0.008$), and tibial internal rotation ($r = 0.62$, $p = 0.003$). Femoral internal rotation displayed significant intra-joint relationships with knee flexion ($r = 0.64$, $p = 0.002$) and knee internal rotation ($r = 0 .99$, $p < 0.001$). Tibial internal rotation was significantly

Table 4-2. Excursions observed during the four different activities.

Variable		Activity Walking	Jogging	Hopping	Jumping
Knee Flexion (°)	Mean	9.3	24.2	36.0	33.2
	SD	5.7	5.0	6.0	8.8
Ankle Dorsiflexion (°)	Mean	7.2	22.4	29.9	43.4
	SD	3.7	9.9	8.2	11.0
Foot Eversion (°)	Mean	3.4	7.3	12.5	15.1
	SD	2.0	3.6	7.5	8.1
Knee Internal Rotation (°)	Mean	6.5	8.9	10.0	9.2
	SD	4.3	3.5	5.4	4.0
Tibial Internal Rotation (°)	Mean	6.9	13.1	17.4	16.6
	SD	3.7	3.8	6.0	6.2
Femoral Internal Rotation (°)	Mean	6.5	7.5	8.3	9.1
	SD	3.9	2.6	2.7	4.1
Rearfoot eversion (°)	Mean	5.1	11.8	14.7	21.2
	SD	2.9	11.3	10.3	16.5

Table 4-3. Inter-joint excursion relationships during the four activities.

Variable		Activity: Walking	Jogging	Hopping	Jumping
KF-DF	r	.49 *	.24	.24	.45 *
	p	.027	.316	.301	.047
KF-FEV	r	.16	.53 *	.13	.02
	p	.49	.019	.581	.921
KF-RFEV	r	.46 *	.09	.04	.02
	p	.04	.71	.878	.933
KF-TIR	r	.56 *	.18	.30	.07
	p	.013	.449	.196	.785
KIR-DF	r	.28	.21	.07	.17
	p	.225	.371	.775	.481
KIR-FEV	r	.23	.03	.01	.19
	p	.332	.90	.965	.413
KIR-RFEV	r	.10	.15	.174	.05
	p	.67	.528	.464	.837
KIR-TIR	r	.19	.45	.04	.33
	p	.191	.047 *	.878	.161
FIR-FEV	r	.25	.08	.09	.03
	p	.286	.734	.709	.905
FIR-RFEV	r	.12	.52 *	.05	.17
	p	.614	.019	.844	.474
FIR-TIR	r	.22	.55 *	.16	.11
	p	.347	.012	.506	.640

Note: KF: knee flexion; DF: ankle dorsiflexion; FEV: foot eversion; RFEV: rearfoot eversion; TIR: tibial internal rotation; FIR: femoral internal rotation; KIR: knee internal rotation. * significant correlation, $p < 0.05$.

Table 4-4. Intra-joint excursion relationships during the four activities.

Variable		Walking	Jogging	Hopping	Jumping
		Activity			
WITHIN-KNEE					
KF-KIR	r	.66*	.18	.26	.07
	p	.001	.449	.261	.785
KF-FIR	r	.64*	.33	.28	.13
	p	.002	.156	.231	.590
KIR-FIR	r	.99*	.68*	.54*	.49*
	p	.000	.001	.014	.028
WITHIN-FOOT					
DF-FEV	r	.75*	.60*	.44	.47*
	p	.000	.005	.053	.035
DF-RFEV	r	.79*	.13	.60*	.07
	p	.000	.574	.005	.757
DF-TIR	r	.73*	.11	.08	.004
	p	.000	.634	.744	.988
FEV-TIR	r	.36	.05	.22	.23
	p	.15	.839	.356	.325
FEV-RFEV	r	.58*	.19	.72*	.11
	p	.008	.432	.000	.640
RFEV-TIR	r	.62*	.10	.029	.23
	p	.003	.675	.902	.338

Note: KF: knee flexion; DF: ankle dorsiflexion; FEV: foot eversion; RFEV: rearfoot eversion; TIR: tibial internal rotation; FIR: femoral internal rotation; KIR: knee internal rotation.* significant correlation, $p < 0.05$.

correlated with knee flexion ($r = 0.56$, $p = 0.013$), ankle dorsiflexion ($r = 0.73$, $p < 0.001$), and rearfoot motion ($r = 0.62$, $P = 0.003$). Knee flexion and knee internal rotation ($r = 0.66$, $p=0.001$), knee flexion and ankle dorsiflexion ($r = 0.49$, $p = 0.027$), knee flexion and tibial internal rotation ($r = 0.56$, $p = 0.013$), and ankle dorsiflexion and foot eversion ($r = 0.75$, $p < 0.001$) were also significantly correlated during walking.

Coupling coefficients were determined to identify the relationship between foot movement and tibial rotation and foot movement and knee rotation during the four dynamic activities (Table 4-5). Repeated measures MANOVA indicated significant differences among the four activities (Hotellings $T = 5.948$, $F(12,8) = 3.966$, $p = 0.030$). Univariate tests indicated that the eversion / tibial internal rotation ratios ($F(3,57) = 4.67$, $p < 0.01$) and eversion / knee internal rotation ratios ($F(3,57) = 6.85$, $p = .001$) were significantly different among the four different activities. Post hoc analyses revealed that the ratio of foot eversion to tibial internal rotation during jumping was significantly greater than during jogging ($p = 0.006$). There was also a trend for the ratio during jumping to be greater than walking ($p = 0.07$). The eversion-knee internal rotation relationship was significantly greater in jumping compared to walking ($p = 0.004$) and jogging ($p = 0.007$). However, the ratios of rearfoot motion to tibial rotation and knee internal rotation were not significantly influenced by the type of dynamic activity.

Discussion

During dynamic activities such as running and landing from a jump, the lower extremity joints must work together to dissipate the impact forces generated when the body makes contact with the ground. A lack of coordination among these joints can lead to antagonistic kinematics and injury. Movement coupling between the foot and shank

Table 4-5. Coupling coefficients during the four activities.

Variable		Activity: Walking	Jogging	Hopping	Jumping
FEV / TIR	Mean	.57	.61	.87	1.03
	SD	.38	.34	.71	.57
RFEV / TIR	Mean	.81	.93	.95	1.76
	SD	.43	.85	.76	2.93
FEV / KIR	Mean	.76	.97	1.67	1.94
	SD	.64	.59	1.67	1.32
RFEV / KIR	Mean	1.24	1.45	1.94	1.76
	SD	1.28	1.2	2.07	2.93

Note: FEV: foot eversion; RFEV: rearfoot eversion; TIR: tibial internal rotation; KIR: knee internal rotation.

resulting in internal tibial rotation has recently been associated with running injuries (McClay & Manal, 1997; Nigg et al., 1993; Stergiou et al., 1999) and a disruption of the ACL during landing and cutting maneuvers (Hess et al., 1994). Recent studies have investigated the ratio of foot eversion to tibial rotation during running. However, there are no published studies investigating the relationship between eversion and tibial internal rotation during landing or how this relationship may change depending on the dynamics of the activity. The results of the present study indicate that the ratio of foot motion to internal tibial rotation and the associated movements of the lower extremity joints are dependent on the nature of the task.

The movement coupling coefficient is the variable used to describe the coupling mechanism between foot eversion and tibial rotation. The use of the coupling coefficient assumes there is a direct coupling between foot motion and internal rotation of the tibia and subsequently the knee during dynamic activities (Nigg, 1993). This assumption is supported both by theoretical considerations (Inman, 1976; Tibero, 1987) and in vivo studies of ankle joint complex kinematics during walking and running (McClay & Manal, 1997). However, the coupling of foot motion via either rearfoot or whole foot motion to axial rotation of the tibia has not been measured during landing from jumps. The results of the present study indicate that the coupling coefficient changes as the loads on the lower extremity increase. The coupling coefficient was observed to increase significantly from the locomotion to landing tasks. This finding suggests that the role of foot motion in dissipation of the impact forces increased; though the increased foot motion is not transferred up the lower extremity kinetic chain. Thus, attempting to control transverse plane motion at the knee via controlling foot motion may not be as effective as once

thought. The present coupling coefficients compare well with in vitro studies and those using skin and shoe mounted markers, which ranged from 0.2 to 1.53. Because of the large range of values reported in the literature, it is important to keep in mind the methodological discrepancies in the literature when comparing coupling coefficients among studies. For example, McClay and Manal (1997) reported an average coupling coefficient of 1.29 for shod running. In the present study, subjects jogged barefoot at a moderate self selected pace. Previous literature has indicated that in barefoot running the foot possesses a decreased maximum eversion velocity and reduced total eversion compared to shod running. Thus, the larger coupling coefficient observed in the McClay and Manal (1997) investigation may be a result of the greater amount of eversion and reduced amount of tibial rotation.

In all four activities, knee internal rotation excursions were less than the tibial internal rotation excursions, which is in accord with previously reported results (McClay & Manal, 1997). The difference between knee and tibial internal rotation has been hypothesized to be a result of femoral rotation. Femoral rotation can compensate for excessive tibial rotation, thereby minimizing the increase in the resultant rotation at the knee (McClay & Manal, 1997; Tibero, 1987). The present results support this hypothesis. The difference in tibial rotation and knee internal rotation increased as the intensity of the activity increased. Knee internal rotation increased from walking to jogging but essentially remained the same during jogging and landing from a hop and a jump while the amount of femoral excursion increased as activity increased. This pattern indicates that as the demands of the activity increase, the femur follows the tibia in an attempt to reduce demands of the rotary stabilizers of the knee. Though this may be a protective

mechanism for the internal structures of the knee, it may lead to other knee disorders (Tibero, 1987).

The measured values of lower extremity motion in this study are comparable to measurements taken in other studies (McClay & Manal, 1997; Reischl et al., 1999). During running, McClay and Manal (1997) reported the following excursion values: knee flexion, 27.1°; knee internal rotation, 8.9°; tibial internal rotation, 8.9°; and rearfoot eversion, 12.7°. The mean values observed in the present study for these excursions were 24.2°, 8.9°, 13.1°, and 11.8°, respectively. Further, the values of knee flexion and ankle dorsiflexion observed during the hopping and jumping tasks in the present investigation are similar to those reported in Table 3-2 for similar tasks.

As mentioned, the lower extremity joints must function to dissipate the forces incurred during the impact phase. Another way of investigating the coupling of these joints is to compare the correlative nature of inter-and intra-joint excursions. Significant inter-joint correlations were observed between associated movements such as knee flexion and foot eversion and ankle dorsiflexion and foot eversion. These movements function together to serve as the cushioning mechanism of the lower extremity. McClay and Manal (1997) observed a similar pattern during running. Conversely, Reischl et al. (1999) reported that the magnitude of peak foot pronation was not a significant predictor of the magnitude of either tibial rotation or the magnitude of femoral rotation during the stance phase of walking. The present results support this contention, though rearfoot eversion was significantly correlated to femoral internal rotation during jogging. Of the nine intra-joint correlations investigated, eight significant relationships were observed during the walking tasks. However, there were only two significant intra-joint

correlations in the jogging and jumping trials and three in the hopping tasks. The most consistent relationships were between ankle dorsiflexion and foot eversion followed by knee internal rotation and femoral internal rotation. This finding supports the complimentary roles of dorsiflexion and eversion in shock absorption. The significant correlation between femoral internal rotation and knee internal rotation supports the notion that the femur follows the tibia to reduce the rotary demands on the knee joint (Tibero, 1987). Regarding the relationship between frontal plane movement of the foot and transverse plane rotation of the tibia, no significant correlations were found between foot eversion and tibial rotation during the four tasks. However, rearfoot eversion was significantly correlated to tibial internal rotation in walking.

Conclusions

This investigation explored coupling relationships in the lower extremity and compared these among four different functional tasks. The findings suggest that the coupling coefficients increased as the forces imparted on the body increased. This suggests that the role of foot motion in shock absorption increased; however, the increased foot motion was not translated to the tibia and knee. Further, the changing nature of the coupling coefficient implies that different and distinct coupling mechanisms may exist depending on the movement task. The present study also confirms that ankle joint coupling with the foot and tibia is far more complex than a mitered or universal joint. The magnitude of internal tibial rotation was found to increase from the locomotion to landing tasks while the magnitude of knee internal rotation remained essentially unchanged. This observation suggests that femoral rotation can compensate for excessive internal tibial rotation. Correlation analyses revealed significant relationships between a

number of inter- and intra-joint relationships, however, the majority of these relationships were dependant on the nature of the activity.

Future studies should investigate the association between these coupling coefficients and likelihood of injury in running and landing activities. Further, the influence that clinical manipulations aimed at controlling knee motion by mitigating excessive motion of the foot have on these coupling relationships should also be investigated.

CHAPTER 5
GENERAL DISCUSSION AND CONCLUSIONS

Female participation in sports has increased exponentially since federal legislation mandated equal opportunities and funding for female athletics. Females now have a greater variety of sports to choose from and an increased number of hours in which to participate. However, the increased exposure has been accompanied with an increased incidence of injury. Interestingly, the overall frequency of athletic injuries among females is nearly equal to their male counterparts with one exception, knee injuries. In fact, females are up to eight times more likely to suffer a knee injury (Harmon & Ireland, 2000). Injuries to the musculoskeletal system can occur in one of two ways. First, a one time event with sufficient magnitude can cause disruption of the tissue leading to injury. Second, injury can occur as a result of sub-threshold events occurring in a repetitive nature at a frequency that does not allow the body to remodel (Winter & Bishop, 1992). The knee is particularly susceptible to both mechanisms of injury as observed during landing from a jump and running (James et al., 1978). The purpose of this two-study investigation was to examine the lower extremity kinetic chain during locomotion and landings in regards to factors related to knee injury in female athletes.

As mentioned, the popularity in female athletics continues to grow. Females are beginning to participate in sports as early as four years of age. However, injury epidemiology suggests that if female athletes continue to participate in sports beyond

puberty, they are increasingly susceptible to knee injury (Backx et al., 1989). The majority of knee injuries in female athletics occur in jumping and cutting sports such as soccer and basketball (Harmon & Ireland, 2000). In these sports the jump-landing sequence has been identified as a common mechanism of injury (Gray et al., 1985). Perhaps female athletes after progressing through puberty perform landing sequences in a manner that makes them more susceptible to injury than prepubescent athletes. The results of Study I support this hypothesis. The results of this investigation indicated that the group of prepubescent athletes landed in a slightly more flexed position, flexed the lower extremity less and over a shorter time duration in the landing phase of a jump than the postpubescent athletes. Both groups experienced similar extensor moments though the prepubescents relied on greater eccentric muscle power than the postpubescent athletes to dissipate the ground reaction forces. The postpubescents made use of a landing strategy (less flexed landing position) that allowed for the greatest range of motion available to dissipate the kinetic energy of landing. However, this more erect position may place the ligaments within the knee capsule at risk due to the reduction in the moment arm of the hamstrings resulting in an increased loading of ACL. The significant maturation by jump type interactions observed for various dependent variables indicated that the two groups respond differently depending on the nature of the jump-landing activity. The possible relationship between these differences and the increased susceptibility to injury warrants further research. However, training and rehabilitation specialist should consider these differences when designing conditioning and rehabilitation programs for these athletes.

During ballistic activities such as running and landing from a jump, the lower extremity joints must function in a coordinative manner to dissipate the impact forces generated during ground contact without causing injury. Concurrent subtalar pronation, ankle dorsiflexion, and knee flexion are associated with the attenuation of these impulse shock loads. However, asynchrony in the time or magnitude of the motion between the knee, ankle and subtalar joint may lead to an antagonistic relationship and increased susceptibility to injury (Stergiou et al., 1999). The relationship between the magnitude of foot motion and rotation of the tibia has been studied previously in walking and running (McClay & Manal, 1997; Reischl et al., 1999). This relationship has been found to be dependent on several factors including the amount of ankle dorsiflexion and the ground reaction forces generated during the activity. Surprisingly, no attempt has been made to investigate the coupling of motion between the foot and knee during landing from a jump or other factors that may influence the coupling of motion such as speed of locomotion. The purpose of Study II was to investigate the coupling of motion among the foot, tibia, and knee during landings as a potential mechanism of knee injury in female athletes. Further, Study II determined that the coupling of motion in the lower extremity joints is dependent on the activity performed. Indeed the results of this investigation suggest that direct coupling of motion between the foot and the tibia and subsequently the knee was directly influenced by the activity. The coupling coefficient was observed to increase significantly from the locomotive to landing tasks. This finding suggests that the role of foot motion in dissipation of the impact forces increased though the increased foot motion is not transferred up the lower extremity kinetic chain. Thus, attempting to control transverse plane motion at the knee via controlling foot motion may not be as effective as

once thought. Another way of investigating the relationship between joint motions is to compare the correlative nature of inter- and intra-joint excursions. Significant inter-joint correlations were observed between associated movements such as knee flexion and foot eversion and ankle dorsiflexion and foot eversion. These movements function together to serve as the cushioning mechanism of the lower extremity. However, the majority of other intra- and inter-joint relationships were dependent on the nature of the activity. For example, of the nine intra-joint correlations investigated, eight significant relationships were observed during the walking tasks. Conversely, there were only two significant intra-joint correlations in the jogging and jumping trials and three in the hopping tasks. In conclusion, the results imply that distinct coupling mechanisms exist that are dependent on the movement task. Further, the present study also confirms that ankle joint coupling with the foot and tibia is far more complex than a mitered or universal joint.

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APPENDIX A
STUDY I: RAW DATA

Peak Forces

04 2 -29.9 36.5 -17.6 0.4 -0.3 4.1 -16.8 -15.4 -33.5 -30.4 37.9 -17.5 -3.1 3.3 3.2 -18.0 -14.9 -34.0 -34.4 42.7 -18.2 0.2 0.2 3.6 -19.5 -15.0 -38.4 -18.8 24.1 -11.9 1.9 -0.2 1.6 -11.4 -12.7 -20.6 -21.3 26.6 -13.9 2.0 -0.0 2.2 -13.4 -14.4 -23.6 -20.8 25.9 -12.8 -0.1 -2.1 1.6 -12.6 -10.9 -24.0

05 2 -58.6 37.9 -13.6 -23.4 9.5 -2.5 -40.0 -11.3 -32.7 -37.1 43.3 -13.5 -12.4 12.8 -3.1 -8.9 -11.3 -40.0 -40.1 44.9 -16.8 -7.3 7.7 -2.8 -11.0 -12.8 -41.1 -18.4 18.2 -11.4 -7.9 7.8 -1.8 -5.6 -10.8 -16.8 -22.9 24.6 -13.0 -7.4 7.9 -2.7 -6.1 -9.4 -21.1 -23.7 26.4 -14.0 -3.2 3.6 -2.7 -7.9 -9.9 -22.8

07 2 -28.0 37.3 -11.4 10.4 -11.8 -4.2 -18.1 -8.7 -34.6 -32.4 41.7 -13.3 10.5 -11.3 -4.5 -18.5 -8.8 -38.5 -36.0 42.3 -15.0 -3.5 3.5 -4.7 -16.0 -11.9 -38.3 -17.8 23.6 -11.8 8.8 -9.5 -3.1 -10.1 -7.0 -19.4 -16.8 23.0 -12.0 8.0 -8.6 -4.3 -10.4 -6.8 -18.5 -22.9 28.9 -15.4 8.7 -9.5 -3.7 -10.9 -5.1 -23.0

09 2 -38.3 43.9 -13.5 -8.2 9.0 -5.1 -11.4 -11.5 -40.6 -36.4 40.6 -11.5 -7.5 7.7 -6.7 -9.3 -13.6 -37.4 -48.7 53.3 -15.3 -7.9 7.9 -6.4 -9.2 -12.6 -49.3 -24.9 29.4 -10.9 -5.6 6.1 -4.5 -8.4 -10.6 -25.3 -22.0 25.0 -10.9 -6.6 6.5 -5.9 -8.7 -10.4 -23.1 -27.6 32.4 -11.9 -5.6 6.0 -5.9 -9.6 -10.2 -30.6

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18 2 -32.8 38.5 -13.5 -4.8 4.7 2.0 -14.9 -14.6 -37.0 -34.7 40.2 -13.6 -8.0 8.7 -2.1 -12.4 -15.3 -38.7 -36.9 43.2 -15.0 -8.0 9.0 0.1 -14.3 -14.7 -40.8 -17.3 17.6 -10.6 -4.1 4.0 1.8 -9.0 -12.1 -16.9 -20.1 20.6 -11.8 -6.6 7.1 -3.1 -9.3 -13.0 -20.5 -24.1 25.4 -14.3 -6.2 6.5 -2.0 -8.0 -11.1 -22.9

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05 1 -41.5 46.3 -30.4 -4.8 4.9 -5.8 -12.7 -13.0 -43.0 -51.7 57.4 -29.3 -7.0 7.2 -6.3 -12.8 -11.9 -53.7 -49.0 53.8 -27.1 -5.7 6.0 -5.5 -11.5 -11.7 -50.4 -27.6 30.8 -19.2 -3.2 3.2 -3.7 -7.8 -6.3 -25.5 -26.0 29.1 -21.0 -3.6 3.7 -5.4 -8.7 -7.9 -23.2 -27.3 30.1 -20.1 -3.0 3.3 -5.0 -6.0 -7.0 -23.7

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Peak Moments

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07 2 9.6 -7.6 -6.6 2.9 2.6 -1.5 -2.1 1.7 -4.9 11.8 -9.4 -6.6 2.4 2.5 -2.4 -2.7 2.3 -7.1 15.4 -13.4 -12.4 -3.9 -3.5 -2.2 2.0 2.3 -6.1 5.7 -4.5 -2.6 3.0 2.0 -2.2 -1.8 1.8 -3.6 6.3 -5.2 -3.2 2.3 -0.2 -2.5 -2.2 2.4 -4.1 8.0 -6.7 -4.7 3.4 0.7 -3.0 -2.1 2.0 -5.0

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23 2 8.7 -7.2 -7.2 2.8 2.9 -1.0 1.3 1.0 -1.8 10.5 -8.7 -8.4 2.9 1.4 -1.8 -0.0 1.8 -
3.8 15.0 -14.1 -13.9 -8.8 -8.8 -4.5 -0.2 3.3 -10.4 2.7 -2.0 -2.0 1.7 2.1 -0.6 1.4 1.0
0.5 10.5 -9.3 -7.9 -3.8 -4.3 -4.0 -2.3 3.8 -6.5 9.3 -8.8 -7.4 -4.0 -4.2 -3.5 -1.5 2.5 -5.2

08 1 3.8 -3.4 -3.0 9.9 10.5 4.7 4.8 -3.0 10.4 5.4 -5.3 -3.7 10.4 11.0 5.7 5.1 -3.6
11.1 6.1 -5.3 -4.5 5.6 6.0 3.1 2.7 -1.9 5.7 -4.9 5.8 5.8 4.0 5.1 1.8 4.0 0.1 5.5
-2.9 3.8 4.9 3.6 4.3 2.0 2.9 -1.7 3.8 -0.2 2.1 3.0 9.1 10.1 4.1 5.1 -2.0 9.1

08 2 4.8 -4.7 -4.6 8.4 9.5 4.0 4.5 -3.0 8.6 3.1 -2.6 -2.8 6.3 6.6 2.5 2.8 -2.7 6.3
2.2 2.7 2.6 5.0 5.6 2.0 2.0 -1.9 5.7 -3.2 4.7 2.6 7.0 8.7 3.6 5.2 -2.1 8.7 5.1 -
4.6 -5.4 8.8 9.7 3.9 4.3 -2.0 8.1 3.1 -2.3 -3.1 5.9 6.5 3.5 3.0 -1.8 4.9

13 2 7.5 -6.1 -5.9 8.3 8.8 2.6 2.8 -1.1 7.3 7.4 -6.0 -5.3 8.1 8.5 2.5 2.5 -1.0 7.1
6.7 -5.5 -5.1 5.9 6.5 2.1 2.0 -1.0 5.5 3.8 -2.7 -2.6 7.9 8.5 3.8 3.0 -1.4 7.2 0.1
1.2 -0.6 -1.3 -2.4 -1.8 3.8 2.6 4.8 5.0 -4.3 -3.6 3.6 3.8 1.6 1.6 -0.7 2.4

14 2 6.3 -5.7 -5.4 4.5 5.0 2.7 2.9 -2.2 5.3 6.0 -5.0 -4.8 2.5 3.0 1.7 2.1 -1.4 2.9
8.5 -7.3 -6.7 4.5 5.5 2.5 2.8 -2.0 5.5 6.3 -5.4 -4.3 5.0 5.8 3.3 3.3 -2.2 5.7 4.4
-3.8 -3.4 3.4 3.9 2.5 2.2 -1.5 3.6 7.1 -5.5 -6.1 5.2 5.8 3.4 2.6 -1.8 5.2

15 2 10.3 -8.9 -4.4 12.4 13.0 4.1 4.2 -3.1 13.5 8.8 -7.3 -4.5 9.4 10.2 2.6 3.7 -3.1
10.3 10.6 -9.3 -5.2 11.7 12.5 3.9 3.5 -2.4 12.8 5.5 -4.6 -1.2 4.9 5.6 2.1 3.3 -2.5
5.3 6.5 -5.4 -3.8 3.0 3.4 1.6 2.0 -1.1 3.2 5.3 -4.5 -3.1 4.6 4.7 2.6 2.0 -1.3 4.1

Peak Powers

04 2 -98.9 127.0 0.2 -12.5 3.4 1.2 -125.9 138.0 3.8 -23.9 11.4 2.0 -115.9 110.0 8.3 -19.7
10.8 19.5 -51.9 34.9 3.0 -7.8 4.8 1.1 -38.4 15.0 5.5 -12.6 8.9 -9.6 -5.7 -23.3 6.6 -9.3
6.4 16.2

05 2 -76.1 99.5 -34.9 -8.4 -16.2 -5.4 -34.0 67.6 -24.9 -5.1 -4.3 -1.9 -62.0 82.7 -13.0 -6.6
3.3 1.2 -5.4 9.6 4.4 -0.8 2.1 -1.4 -0.2 18.1 -9.0 -5.7 2.8 -1.0 -23.2 -0.6 0.1 -6.8 5.5
1.5

07 2 -40.7 57.9 -12.6 -7.7 6.7 -8.2 -52.4 61.4 -11.2 -10.5 12.1 -6.5 -103.6 105.0 7.7 -10.7
5.7 -6.8 -19.7 16.7 -8.9 -7.8 7.0 0.2 -25.2 13.9 0.6 -11.7 8.3 0.2 -25.0 25.3 -2.6 -14.5
9.1 0.9

09 2 -38.1 82.4 -18.8 -12.0 0.7 -8.7 -38.9 58.9 -6.5 -9.6 4.0 -8.3 -71.8 86.3 -17.7 -13.1
0.7 -4.1 -21.2 19.3 -5.3 -4.2 1.8 -4.0 6.6 2.6 -8.5 -9.2 4.4 0.3 -45.8 -32.5 -5.6 -9.9
4.2 7.0

10 2 -43.4 39.9 8.6 -12.4 6.6 9.2 -47.9 28.1 5.3 -10.0 8.3 9.7 -44.5 31.4 11.1 -10.8 9.6
15.0 -19.5 -0.9 0.1 0.7 2.5 -1.3 -27.7 10.5 3.9 -4.6 5.7 -8.1 -30.8 -3.4 10.5 -9.1 6.0 -
20.6

18 2 -83.2 84.8 5.8 -14.0 -5.1 7.8 -67.9 73.3 -0.0 -18.4 -9.0 9.2 -87.1 97.3 -6.8 -15.4 -4.6
10.1 -2.5 8.7 -0.0 -2.6 1.8 -0.1 -7.5 1.9 9.5 -5.6 5.7 -4.5 -30.8 -26.4 1.8 -5.6 -1.2 -
5.3

03 1 -32.4 112.8 -49.7 -6.2 5.4 -3.0 -79.0 92.7 -30.1 -24.8 24.2 -12.5 -124.3 143.1 -20.8 -16.5
14.2 -9.4 -25.6 -17.9 -7.5 -6.6 10.8 2.9 -25.6 -7.5 -3.3 -23.1 17.9 -9.2 -43.5 -53.9 -13.1 -
23.0 20.1 12.6

04 1 -53.3 56.5 9.1 -13.6 14.7 -29.9 -57.4 64.8 5.1 -18.1 14.5 -25.7 -39.6 54.2 2.5 -8.2
5.4 -19.2 -10.4 10.7 5.2 -7.4 8.6 -5.6 -21.5 -6.2 7.9 -7.4 8.0 -8.1 -50.9 -37.3 8.7 -5.3
9.5 -6.4

05 1 -47.5 134.3 5.1 -42.9 6.0 -45.6 -77.0 151.4 -4.0 -33.6 5.8 -53.9 -72.8 155.7 -11.3 -27.2
8.2 -37.2 -20.5 51.9 -5.5 -22.8 4.3 -9.9 -31.2 83.0 -0.7 -27.2 6.5 -7.8 -24.9 48.9 1.3 -18.1
4.0 -12.6

06 1 -58.6 119.8 6.5 -2.0 2.9 -11.3 -148.2 174.2 -1.0 -6.9 7.5 -0.2 -70.9 107.3 4.4 -9.1
8.3 -6.5 -8.1 -1.9 0.4 -1.8 5.3 1.9 -12.7 -0.2 8.9 -12.3 8.4 9.3 -23.8 0.2 8.8 -12.2
9.7 15.6

09 1 -57.7 66.9 12.4 -9.9 11.0 -28.1 -69.5 84.9 1.3 -7.1 10.3 -16.8 -33.8 43.3 3.4 -6.7
7.1 -11.1 -6.8 5.8 4.7 -7.7 8.8 -4.1 -10.5 12.5 5.3 -10.3 9.4 -5.2 -14.7 9.4 -0.5 -1.6
5.3 -1.2

10 1 -82.5 70.2 13.4 0.1 6.8 -8.9 -80.0 100.8 1.3 1.8 7.0 -2.0 -46.7 64.6 10.3 -4.3 4.6
-16.0 -8.2 2.4 4.2 -2.8 6.4 4.5 -19.8 10.8 11.8 -5.3 0.8 8.6 -11.9 10.9 10.7 6.0 7.0
1.3

11 1 -31.1 35.1 -8.1 -2.6 3.5 -6.5 -45.9 40.9 -0.5 -4.0 4.8 -13.0 -28.2 34.6 -8.9 -2.1 3.7
-2.9 -8.2 -0.5 1.9 -1.2 2.6 6.5 -24.7 -21.0 2.9 7.1 -4.9 9.9 -27.4 5.3 7.5 -5.5 4.4
0.7

12 1 -44.4 30.5 -18.1 3.9 3.9 6.8 -112.3 96.4 -6.4 2.2 3.1 12.2 -131.2 120.6 -16.9 10.0 4.6 7.0 -5.9 8.4 6.9 0.8 -0.9 9.8 11.7 -2.3 8.1 -5.7 -0.2 16.1 -17.4 -6.0 2.9 -8.7 -6.7 24.7

13 1 -52.2 67.2 6.2 -3.0 7.5 -16.0 -85.7 108.3 20.2 -14.0 12.0 -38.9 -100.3 52.5 25.5 -10.6 12.2 -25.8 -7.3 21.3 1.9 -3.6 6.4 17.2 -13.4 -5.4 4.4 -5.4 1.7 19.3 -17.9 -35.4 7.8 -5.0 -0.3 32.7

14 1 -57.7 64.4 34.2 -10.4 5.3 -29.1 -115.9 161.1 27.1 -17.0 -1.2 -31.8 -74.2 82.8 19.7 -11.6 5.2 -24.8 -53.2 -39.8 -3.6 -6.0 8.1 4.5 -42.1 -8.1 12.5 -14.3 4.8 3.6 -47.9 -51.6 -4.8 -6.3 -4.6 19.5

15 1 -135.5 150.0 -2.7 -1.3 4.1 -11.7 -128.8 180.2 -0.7 -8.0 4.7 -23.0 -102.6 126.3 -0.5 -9.9 9.4 -18.5 -8.0 0.0 -1.0 -3.7 6.9 -1.1 -22.9 -29.2 1.6 -6.2 6.2 7.8 -24.6 -24.0 8.9 -7.8 11.2 10.3

16 1 -22.3 12.0 -4.3 2.0 -0.2 9.4 -38.2 37.1 1.9 2.7 0.6 6.5 -19.8 30.4 4.5 -3.6 2.5 -5.1 -8.7 1.5 -0.6 0.2 1.3 -0.9 -7.4 4.7 1.5 -2.6 1.7 1.2 -20.4 -13.7 1.9 -0.4 1.2 3.0

19 2 -32.9 40.8 1.9 -8.4 3.8 5.8 -50.3 51.9 17.0 -20.6 0.6 12.9 -47.3 50.2 9.7 -11.5 4.2 11.1 -27.4 -32.7 5.2 -9.0 4.7 -12.6 -38.0 -27.4 -10.8 -13.0 -0.5 -11.9 -8.4 -3.4 2.1 -6.9 2.9 -12.1

20 2 -26.6 33.4 -4.5 5.5 -0.0 7.2 -34.5 51.8 5.9 -6.3 3.2 -23.0 -61.1 79.8 19.6 -7.9 1.7 -41.2 7.7 -9.9 1.9 4.0 1.6 4.9 -16.6 -29.3 5.4 2.1 2.6 28.1 -21.5 -40.7 5.5 -0.5 2.3 22.6

21 2 -71.4 109.2 1.5 1.0 0.8 -0.1 -99.3 128.7 -14.4 -14.3 -7.0 -14.7 -60.2 84.7 -1.9 -13.7 3.8 -13.1 -59.8 100.1 5.8 11.9 -4.0 2.8 -104.2 95.5 11.4 -15.1 12.5 -23.3 -105.2 113.8 7.5 -10.4 9.0 -7.1

23 2 -40.0 82.0 -10.6 -1.2 4.8 -3.4 -55.2 107.6 -4.8 -15.1 7.1 -8.4 -66.4 95.2 0.4 -33.5 -1.9 -0.3 -7.9 5.7 -4.1 -2.9 4.7 0.6 -44.2 37.8 10.6 -32.3 12.9 17.6 -33.2 14.3 1.0 -14.7 9.3 9.3

08 1 -20.4 27.4 -25.4 28.4 -12.1 16.5 -30.7 45.6 -24.4 49.8 -12.6 20.7 -31.2 41.6 -11.5 14.7 -7.1 7.8 26.8 -25.6 -10.1 8.4 1.0 3.9 20.8 -37.3 -9.3 12.1 -6.7 4.6 9.3 -15.7 -4.2 16.7 -7.9 -5.9

08 2 -29.4 57.4 -17.0 21.4 -6.5 7.0 -11.2 31.2 -11.7 14.1 -6.5 5.5 14.8 21.9 -14.8 12.5 3.1 -5.4 26.7 -17.8 -15.0 17.3 -4.2 -4.0 -21.1 10.2 -16.2 24.0 4.7 -17.6 -12.4 28.0 -17.3 21.0 -4.6 -9.5

13 2 -38.6 45.0 -12.6 12.0 -4.3 7.5 -40.2 50.7 -15.4 16.3 -4.4 7.6 -39.6 46.7 -13.7 9.6 -2.6 8.2 -11.7 17.5 0.9 20.2 -0.4 0.3 -12.5 5.2 -27.1 13.5 5.6 -15.5 -16.5 -14.0 -7.1 4.8 -2.8 -6.1

14 2 -43.2 63.1 0.9 13.6 -4.9 -15.4 -40.8 49.4 -1.5 7.3 -2.5 -8.3 -57.1 80.6 4.5 12.8 -4.7 -14.3 -36.7 32.7 -3.3 16.7 -2.5 -16.6 -25.1 27.9 0.6 12.8 -2.9 -12.2 -21.1 30.4 -3.2 14.1 -3.0 -13.9

15 2 -67.2 44.2 23.1 22.1 -8.0 23.6 -69.7 43.4 18.0 11.9 -2.0 21.2 -72.7 39.3 22.1 23.6 -6.9 13.8 -19.5 1.6 5.2 4.0 2.2 -0.4 -23.1 9.6 -1.0 3.5 2.8 0.2 -22.9 -11.9 -6.0 7.7 -3.4 -6.0

APPENDIX B

STUDY II: RAW DATA

Angular Excursions

02 49.42 35.88 5.25 10.24 -3.93 6.61 3.06 12.14 5.76 -2.11 -4.12 -20.17 -4.95 -7.72
37.28 29.71 6.81 12.17 15.85 10.47 9.41 37.08 32.56 8.45 -4.65 -0.95 -6.85 3.72 12.91
-3.22 -7.41 -19.81 -16.58 -22.03 -9.40 22.54 12.14 5.22 4.93 10.05 4.12 5.25 38.38 38.62
9.27 7.16 -4.60 5.99 -0.70 7.76 -0.32 -0.83 -5.81 -18.53 -7.57 -6.54 30.63 38.80 7.89
11.44 11.60 12.56 5.05 44.12 25.13 6.80 21.23 -1.73 20.54 6.45 -24.70 1.03 -5.22 -24.22
-9.88 -26.41 -7.12 9.86 2.62 0.55 10.27 1.26 10.14 0.47

03 57.61 33.26 -1.94 -14.33 23.21 -11.26 -10.82 20.56 -8.47 -19.76 -24.36 11.28 -22.35 -
31.85 37.06 40.79 17.00 10.03 7.87 10.74 20.76 41.80 32.86 -10.24 -13.98 24.65 -11.32 -
35.79 14.20 -16.20 -25.73 -27.30 9.28 -26.25 -97.29 21.72 17.76 7.85 10.65 13.70 11.41
54.48 41.28 33.89 -4.94 -9.77 28.32 -7.54 2.69 14.87 -7.06 -25.76 -20.59 13.43 -19.28 -
16.38 25.52 40.72 20.81 9.27 12.01 10.70 17.20 33.87 25.55 -7.11 -25.26 29.34 -24.56
10.19 2.17 0.12 -12.97 -33.03 17.16 -32.97 -13.72 1.14 2.65 0.74 2.53 2.94 2.55 1.75

04 37.64 36.17 -5.44 20.44 -15.74 18.36 -5.25 1.96 3.71 -23.33 12.80 -34.12 7.19 -18.14
35.68 29.24 17.30 4.93 16.40 10.61 11.76 36.28 42.83 -6.46 19.16 -14.30 17.78 6.45 -
1.65 -0.50 -22.93 -2.25 -34.12 -13.81 -13.89 26.54 19.85 8.47 4.62 10.17 4.35 8.41 27.01
44.10 -0.17 23.42 -16.24 22.08 0.00 -6.27 3.78 -22.10 13.29 -34.45 11.44 -19.30 33.28
39.85 21.65 8.18 15.41 8.78 19.31 32.45 38.30 -10.15 35.69 -13.52 32.53 10.50 -34.32
11.27 -27.69 -3.23 -29.42 -7.62 -16.67 22.77 5.70 3.54 17.62 6.20 15.39 4.60

05 58.50 24.66 -11.63 11.04 1.73 14.41 -10.25 14.90 -8.74 -29.65 4.81 -10.69 5.84 -21.12
43.61 32.52 16.77 6.23 12.42 7.51 9.64 38.67 33.43 -7.07 9.69 15.32 11.85 3.85 10.58
-15.08 -27.47 -3.23 -8.27 -2.96 -46.70 28.10 15.38 7.11 5.26 9.70 6.47 20.54 52.58
33.94 -4.19 10.01 8.45 14.13 3.76 3.52 -16.08 -35.05 1.14 -15.35 0.75 -15.73 49.06 49.82
30.86 8.87 23.77 13.38 19.49 37.16 27.28 -8.77 4.35 23.78 4.32 38.29 2.71 -4.04 -19.29
-10.22 0.54 -5.98 -17.64 14.45 7.63 1.87 5.99 10.82 5.92 7.72

06 36.76 52.51 7.25 12.84 -12.18 9.64 19.46 2.26 7.05 -31.70 5.77 -27.72 0.42 -32.95
34.50 44.01 37.78 5.13 15.53 6.02 51.18 29.16 46.47 -0.19 6.56 -8.69 4.39 41.04 0.48
-1.96 -17.15 -8.96 -22.27 -10.46 -17.50 28.68 48.15 14.03 10.55 12.85 9.39 21.54 39.68
57.10 3.27 8.90 -12.17 6.87 14.63 2.84 -1.75 -14.99 4.29 -25.56 -2.51 -1.55 36.84 58.76
18.27 4.19 13.38 8.72 16.17 10.53 27.28 -2.96 0.12 -12.51 0.22 8.60 -4.30 5.05 -14.35
-4.04 -19.39 -4.35 -0.36 10.86 13.60 8.33 4.16 6.88 4.57 8.92

07 39.58 28.39 -3.10 27.94 -13.89 17.58 -4.86 5.91 13.75 -11.52 14.61 -24.08 9.51 -13.89
33.67 14.05 7.50 11.32 9.24 7.50 7.75 32.15 49.63 0.97 25.89 3.75 17.71 23.99 2.66
0.53 -18.66 -0.44 -18.88 -1.66 -37.36 29.49 15.94 4.26 12.09 5.04 4.40 2.78 35.19 35.98
2.82 23.39 -13.02 21.67 -0.64 2.52 3.56 -12.97 5.72 -23.41 1.25 -10.52 30.68 32.13 14.96
11.01 8.64 20.39 7.03 5.33 28.47 -0.31 11.82 -9.71 11.74 -3.82 -5.25 8.96 -12.33 2.00
-18.81 1.91 -12.08 5.63 6.87 5.37 7.48 8.17 7.32 7.25

08 43.14 35.15 -10.97 16.59 -14.12 10.38 4.25 7.75 3.78 -18.49 7.09 -26.73 2.93 -11.70
35.39 30.57 7.08 9.50 12.62 7.34 15.95 31.31 33.50 -12.66 6.12 -4.48 5.70 2.31 11.96
-3.25 -22.81 -2.22 -20.76 -2.38 -8.99 18.04 27.65 8.08 4.01 9.73 4.72 7.76 43.87 42.36
-9.03 11.79 -10.29 7.82 -0.15 11.10 -4.83 -19.64 2.41 -29.43 0.90 -17.70 32.76 47.05 9.85
6.41 17.11 3.94 16.51 37.60 27.74 -13.02 0.78 -5.53 0.81 7.24 0.32 4.93 -23.90 -6.19 -
14.34 -6.56 -8.50 0.29 1.53 0.74 0.28 1.15 0.32 1.62

09 55.12 27.18 -0.51 26.42 -3.04 20.51 -3.98 19.76 -5.92 -12.87 17.22 -28.36 9.25 -14.75
35.35 31.45 10.09 8.85 25.23 10.13 10.59 35.52 45.10 -1.14 19.48 13.21 18.56 7.46
3.99 -8.23 -17.70 -4.33 -23.80 -3.45 -16.00 31.53 24.27 8.17 4.29 12.84 4.76 6.18 34.50
48.07 -3.11 16.05 -20.72 12.08 4.92 6.12 -8.92 -39.17 6.51 -48.49 4.48 -12.91 28.03

56.93 35.93 8.65 24.79 7.60 17.27 38.14 33.52 -4.86 4.84 -1.43 5.02 3.47 1.33 3.51 -14.85 -8.23 -12.73 -7.75 -13.95 5.74 4.01 2.20 3.65 4.94 3.68 2.39

10 38.07 59.77 -10.69 21.72 -15.61 19.43 6.54 -1.83 12.72 -27.66 12.11 -40.53 6.65 -7.46 37.83 38.58 12.45 5.55 16.67 9.11 13.64 34.46 51.58 -17.05 23.33 5.02 16.73 9.18 3.38 -7.80 -27.15 -19.46 -24.69 -19.50 -20.01 30.39 43.23 9.95 11.50 15.92 5.23 8.22 53.63 49.62 -14.02 22.92 -8.61 19.50 0.42 -0.04 -14.27 -27.20 13.49 -24.02 11.43 -34.38 53.68 63.88 13.18 9.43 15.41 8.07 34.80 33.32 42.67 -14.85 5.28 2.40 5.27 7.89 -4.24 6.57 -22.82 -12.87 -14.60 -12.95 -14.29 8.85 10.54 4.60 14.89 6.97 15.04 5.14

11 36.34 43.62 2.51 18.11 -26.44 11.92 -5.91 10.36 16.62 -19.78 4.22 -47.21 2.11 -15.78 24.12 17.85 14.33 10.98 13.06 5.13 8.02 36.27 36.50 -0.69 19.30 0.28 15.54 15.07 13.03 -11.49 -24.64 0.81 -23.44 -0.83 -17.22 23.24 24.05 12.29 9.74 9.64 9.07 6.04 41.28 38.65 1.29 15.37 -15.89 11.35 -3.80 11.25 -10.89 -20.47 7.97 -28.11 3.56 -15.07 30.03 49.47 20.81 4.36 9.54 5.28 10.96 37.87 38.77 -8.00 10.49 3.87 10.28 53.14 2.05 -1.24 -21.78 -7.00 -13.59 -7.39 -12.46 6.62 4.70 2.48 1.93 4.76 1.85 2.06

12 39.82 32.56 13.97 18.61 2.95 13.37 1.05 11.49 -1.09 4.09 9.41 -17.51 8.58 -22.67 28.34 31.94 9.58 7.88 20.01 4.26 23.40 38.49 37.79 12.01 15.38 12.88 12.93 21.24 15.18 -12.08 1.34 -13.04 -13.52 -11.89 -14.63 14.73 21.92 5.31 10.05 13.26 6.90 9.72 27.42 48.68 4.62 9.46 -11.68 7.32 11.46 3.70 8.39 -14.85 1.75 -36.33 1.63 -11.69 23.72 40.22 16.76 6.10 23.27 4.70 22.85 57.94 31.98 13.46 4.86 11.02 5.52 26.97 1.91 1.53 2.07 -24.94 -2.49 -24.54 -12.82 13.22 6.69 3.30 6.61 9.58 6.92 5.59

13 41.52 23.67 5.55 18.93 1.45 13.08 0.32 12.35 2.04 -4.84 -0.73 -22.36 -1.87 -8.43 29.17 20.73 9.95 18.90 23.77 12.67 8.63 33.17 26.48 4.97 6.35 11.11 5.37 12.05 8.36 -8.82 -5.56 -28.50 -17.39 -29.06 -5.47 24.81 18.71 6.94 9.84 22.05 8.96 8.49 38.44 31.39 1.11 15.12 3.76 12.02 5.49 3.33 -5.20 -6.16 -4.17 -20.09 -4.20 -11.58 35.11 36.42 6.95 19.29 23.75 15.48 15.81 48.54 28.06 3.50 -5.43 16.83 -5.59 29.74 0.10 1.41 -3.20 -35.33 -0.24 -36.11 -5.30 9.94 6.16 2.18 6.45 9.60 6.45 3.23

14 44.68 35.99 -2.20 12.92 4.84 10.68 -0.77 7.85 -2.44 -11.14 -6.06 -12.55 -5.98 -15.34 36.82 36.81 8.91 12.71 16.98 10.56 13.97 35.20 37.32 -3.97 2.24 11.28 -0.86 13.26 10.53 -10.05 -12.46 -22.91 -8.88 -23.06 -12.45 24.67 20.27 4.02 10.96 12.95 8.27 5.85 56.71 34.72 -1.66 -2.39 2.80 -4.33 124.43 16.51 -9.49 -13.36 -21.44 -6.05 -28.10 -10.33 27.21 30.77 9.10 9.49 6.12 8.43 85.82 45.39 37.61 -3.69 -7.50 7.87 -8.04 36.46 2.09 -0.18 -16.52 -26.09 -6.02 -26.43 -8.17 11.03 9.05 3.71 8.58 11.35 9.03 4.17

15 33.28 41.93 -7.60 24.98 -6.51 21.52 4.22 2.48 4.91 -20.70 1.24 -35.79 0.49 -15.47 30.80 35.74 11.69 9.82 29.28 9.19 19.56 25.02 48.44 -5.48 17.97 -4.60 13.90 25.48 2.20 -3.72 -22.09 -12.23 -30.30 -13.06 -16.70 22.82 28.30 11.47 15.56 19.58 11.64 14.54 23.29 46.57 -6.49 0.75 -6.72 -4.24 7.22 4.89 -1.02 -25.14 -18.43 -30.67 -19.04 -19.16 18.33 47.49 18.43 11.30 23.95 6.70 26.38 36.97 38.69 -9.68 12.37 -7.25 12.38 20.28 -6.93 7.51 -27.39 -10.51 -24.31 -12.18 -14.28 9.20 12.90 6.37 6.76 13.93 6.60 6.07

16 36.26 21.05 14.86 18.57 -9.18 18.67 -8.97 5.61 -0.68 3.76 11.09 -29.42 10.16 -17.02 30.65 17.54 9.84 2.53 20.11 5.49 3.97 27.01 34.46 6.96 18.69 -1.75 18.69 -2.25 0.03 -4.43 -3.30 -1.97 -20.14 -1.13 -17.38 25.71 10.35 5.54 7.41 13.15 6.30 5.93 34.39 15.74 18.08 16.23 -4.08 16.75 -7.46 6.00 -1.69 8.95 7.68 -26.78 8.91 -25.28 28.39 17.41 9.14 8.29 20.97 7.79 16.20 33.89 30.73 5.90 15.42 10.37 14.98 4.05 -5.98 6.05 -6.93 -5.31 -4.48 -4.15 -14.23 10.45 6.99 3.95 8.70 3.34 8.08 3.56

17 52.13 14.16 -3.60 11.44 17.89 14.99 3.63 7.78 -9.72 -18.52 -1.33 -1.11 1.00 -19.32 44.36 21.34 11.69 9.32 18.50 11.02 22.54 41.53 32.18 2.10 3.98 26.24 6.14 21.08 9.70 -15.02 -15.10 -22.25 4.50 -19.78 -6.76 31.83 23.63 13.92 7.14 11.19 7.96 9.71 40.93 39.58 -1.17 7.55 13.19 10.83 14.54 3.79 -12.86 -13.50 -1.81 -1.50 -1.38 -6.34 37.14 52.25

12.29 9.29 13.96 12.04 20.88 48.27 33.34 10.27 -2.01 22.87 -0.98 38.85 -3.67 -5.92 -
12.13 -23.24 10.84 -12.87 -7.52 15.45 8.94 2.62 4.85 10.76 5.91 9.02

18 41.81 38.20 5.99 6.97 8.47 7.90 -7.23 6.52 -0.78 -1.75 -0.61 -13.70 0.08 -23.65
35.29 35.67 3.65 5.22 21.19 5.16 14.97 29.63 47.73 4.84 6.09 16.75 6.51 19.01 5.22
-9.49 -3.53 -21.83 -4.93 -21.69 -23.31 23.73 16.47 5.10 8.95 13.50 9.10 9.96 35.34 29.84
4.89 10.76 7.37 12.73 -8.53 3.65 -4.32 0.01 4.90 -12.26 5.81 -21.18 31.69 33.93 4.13
3.41 17.71 4.81 12.65 33.21 37.53 6.84 -4.98 23.78 -4.93 15.06 -1.35 1.48 -5.31 -17.43
8.68 -16.31 -19.70 4.10 7.68 6.34 6.61 3.87 6.79 6.42

19 67.08 32.02 7.86 21.58 2.96 8.96 1.41 25.20 -5.08 -9.71 -2.42 -22.59 -3.25 -14.59
41.88 35.78 17.57 24.00 25.37 12.21 16.00 36.24 28.14 5.81 10.56 8.75 5.27 0.31
20.03 -6.92 -2.86 -15.83 -16.02 -17.54 -19.70 16.21 17.65 1.24 16.16 17.49 11.84 9.98
66.36 27.78 2.05 17.43 -1.43 5.79 -0.38 17.65 -15.59 -8.69 -0.71 -25.71 -1.59 -21.59 48.71
43.36 10.73 18.14 24.29 7.38 21.21 54.02 25.36 1.90 -7.49 14.28 -9.51 4.23 5.03 -2.78
-2.83 -21.55 0.91 -21.55 -13.72 18.23 15.08 3.77 8.28 12.01 7.38 11.03

20 59.98 19.04 17.30 -1.00 16.94 3.55 1.55 9.75 -11.52 -1.19 -21.91 8.64 -4.20 -5.77
50.24 28.97 17.04 19.14 6.88 7.75 7.32 31.92 43.68 16.20 -12.25 19.26 -9.28 31.18
12.51 -8.39 2.03 -31.84 4.47 -30.91 -15.20 19.41 31.68 3.68 7.14 12.64 9.77 16.66 45.45
41.19 11.38 -12.04 16.51 -9.49 8.57 9.22 -11.94 -1.65 -22.44 5.07 -17.01 -10.70 36.23
52.81 11.89 7.84 7.42 5.06 18.72 35.16 31.37 11.77 -18.68 32.19 -18.44 32.48 6.13 -
2.49 1.05 -36.87 16.91 -32.74 -7.12 3.39 5.33 2.69 2.37 4.12 2.44 7.16

21 51.24 21.14 -15.88 18.18 8.12 17.53 -3.76 13.07 -5.91 -18.68 6.53 -13.05 8.83 -9.22
38.17 25.30 2.28 6.70 21.17 3.97 5.45 29.54 26.23 -12.56 11.04 9.83 12.29 1.70 9.59
-8.48 -20.44 -12.68 -7.62 -10.24 -5.85 19.95 9.66 2.67 6.40 15.74 6.07 4.05 32.06 32.44
-9.96 12.61 9.77 14.30 1.09 5.60 -3.43 -18.33 2.58 -10.95 3.50 -18.58 26.45 35.45 8.30
9.33 19.58 10.36 19.67 30.87 19.22 -13.86 -3.64 16.43 -3.31 4.45 1.24 -1.75 -19.53 -14.70
5.51 -14.12 -6.83 3.62 5.07 2.68 2.61 6.30 2.70 3.32

Time to Excursion

02 0.18 0.01 0.22 0.26 0.00 0.14 0.12 0.00 0.23 0.07 0.01 0.26 0.05 0.09 0.21
0.36 0.21 0.14 0.36 0.00 0.35 0.00 0.19 0.36 0.35 0.21 0.36 0.17 0.20 0.00 0.22
0.09 0.21 0.08 0.22 0.00 0.21 0.02 0.22 0.18 0.21 0.16 0.81 0.37 0.53 0.04 0.81
0.04 0.80 0.02 0.65 0.80 0.31 0.29 0.81 0.57

03 0.20 0.01 0.04 0.12 0.05 0.17 0.15 0.00 0.25 0.26 0.04 0.25 0.07 0.05 0.13
0.28 0.27 0.09 0.29 0.09 0.31 0.28 0.16 0.18 0.28 0.11 0.28 0.14 0.20 0.00 0.20
0.26 0.14 0.24 0.21 0.11 0.21 0.13 0.22 0.21 0.21 0.17 0.76 0.76 0.49 0.34 0.70
0.54 0.76 0.43 0.56 0.62 0.29 0.15 0.45 0.26

04 0.16 0.01 0.20 0.10 0.14 0.17 0.22 0.00 0.24 0.19 0.32 0.18 0.18 0.08 0.20
0.33 0.19 0.18 0.33 0.12 0.33 0.28 0.17 0.33 0.33 0.20 0.33 0.14 0.17 0.00 0.18
0.16 0.14 0.08 0.14 0.11 0.22 0.12 0.31 0.22 0.25 0.08 0.73 0.73 0.37 0.31 0.73
0.49 0.73 0.43 0.51 0.73 0.51 0.21 0.51 0.40

05 0.21 0.01 0.14 0.11 0.14 0.21 0.24 0.00 0.27 0.20 0.13 0.17 0.13 0.04 0.12
0.27 0.23 0.14 0.27 0.11 0.18 0.28 0.14 0.12 0.27 0.11 0.27 0.25 0.26 0.00 0.11
0.14 0.13 0.20 0.14 0.11 0.27 0.15 0.22 0.19 0.16 0.12 0.66 0.66 0.66 0.55 0.66
0.56 0.66 0.43 0.49 0.31 0.66 0.14 0.22 0.15

06 0.17 0.01 0.17 0.14 0.07 0.13 0.20 0.00 0.23 0.05 0.31 0.11 0.26 0.15 0.15
0.27 0.13 0.09 0.27 0.08 0.27 0.28 0.16 0.20 0.28 0.19 0.23 0.23 0.31 0.00 0.27
0.10 0.13 0.09 0.14 0.11 0.31 0.16 0.17 0.10 0.29 0.22 0.53 0.10 0.50 0.13 0.66
0.13 0.48 0.43 0.51 0.10 0.26 0.14 0.10 0.21

07 0.17 0.05 0.29 0.13 0.02 0.16 0.15 0.00 0.21 0.07 0.13 0.11 0.23 0.08 0.13
0.30 0.19 0.12 0.29 0.12 0.28 0.28 0.15 0.27 0.29 0.09 0.29 0.17 0.13 0.00 0.21
0.09 0.12 0.05 0.22 0.22 0.15 0.16 0.24 0.19 0.17 0.16 0.48 0.11 0.42 0.13 0.05
0.13 0.32 0.30 0.46 0.12 0.30 0.21 0.30 0.16

08 0.17 0.05 0.22 0.13 0.02 0.08 0.12 0.00 0.20 0.09 0.18 0.11 0.18 0.08 0.12
0.28 0.10 0.11 0.28 0.12 0.28 0.27 0.14 0.27 0.27 0.12 0.26 0.11 0.20 0.00 0.21
0.22 0.12 0.18 0.12 0.22 0.22 0.09 0.22 0.26 0.29 0.16 0.73 0.73 0.42 0.14 0.72
0.14 0.72 0.27 0.55 0.71 0.47 0.18 0.55 0.28

09 0.21 0.05 0.30 0.09 0.02 0.06 0.15 0.00 0.28 0.08 0.13 0.19 0.24 0.23 0.14
0.35 0.17 0.12 0.35 0.11 0.33 0.27 0.18 0.32 0.32 0.18 0.32 0.24 0.21 0.00 0.17
0.27 0.12 0.15 0.05 0.22 0.23 0.12 0.22 0.27 0.19 0.29 0.72 0.72 0.43 0.07 0.70
0.07 0.71 0.27 0.52 0.70 0.59 0.34 0.59 0.39

10 0.19 0.05 0.26 0.25 0.02 0.09 0.17 0.05 0.32 0.04 0.14 0.29 0.18 0.13 0.14
0.31 0.18 0.12 0.31 0.09 0.31 0.28 0.15 0.32 0.31 0.12 0.31 0.19 0.32 0.00 0.29
0.24 0.12 0.06 0.09 0.22 0.32 0.11 0.22 0.28 0.16 0.06 0.98 0.98 0.47 0.07 0.87
0.07 0.96 0.18 0.63 0.68 0.61 0.17 0.68 0.20

11 0.14 0.05 0.20 0.15 0.02 0.20 0.13 0.05 0.28 0.06 0.05 0.22 0.05 0.15 0.13
0.30 0.16 0.08 0.30 0.08 0.30 0.28 0.15 0.29 0.27 0.09 0.27 0.17 0.21 0.00 0.22
0.17 0.22 0.16 0.07 0.22 0.22 0.11 0.30 0.18 0.24 0.23 0.67 0.67 0.41 0.12 0.67
0.09 0.67 0.18 0.48 0.65 0.44 0.15 0.44 0.41

12 0.17 0.05 0.18 0.20 0.02 0.16 0.17 0.05 0.24 0.07 0.05 0.16 0.08 0.17 0.11
0.29 0.11 0.10 0.29 0.09 0.29 0.26 0.14 0.25 0.29 0.10 0.29 0.15 0.19 0.00 0.24
0.25 0.22 0.16 0.07 0.28 0.23 0.09 0.30 0.26 0.26 0.21 0.67 0.67 0.47 0.13 0.66
0.13 0.67 0.19 0.49 0.61 0.64 0.17 0.65 0.32

13 0.16 0.05 0.13 0.13 0.02 0.15 0.17 0.05 0.23 0.11 0.13 0.16 0.23 0.17 0.12
0.30 0.20 0.09 0.28 0.08 0.29 0.26 0.15 0.20 0.28 0.12 0.28 0.16 0.19 0.00 0.06
0.13 0.12 0.17 0.09 0.28 0.21 0.17 0.30 0.18 0.26 0.17 0.76 0.76 0.47 0.10 0.67
0.10 0.76 0.19 0.54 0.68 0.65 0.13 0.65 0.45

14 0.19 0.05 0.13 0.10 0.12 0.09 0.09 0.05 0.26 0.11 0.32 0.15 0.32 0.15 0.14
0.33 0.14 0.09 0.32 0.08 0.33 0.26 0.16 0.30 0.32 0.09 0.31 0.12 0.13 0.00 0.18
0.12 0.12 0.18 0.11 0.28 0.20 0.13 0.22 0.17 0.23 0.27 0.71 0.71 0.35 0.12 0.65
0.11 0.71 0.19 0.52 0.71 0.43 0.13 0.43 0.36

15 0.15 0.05 0.19 0.10 0.12 0.08 0.05 0.05 0.18 0.09 0.32 0.13 0.32 0.15 0.12
0.32 0.13 0.13 0.30 0.13 0.32 0.26 0.14 0.32 0.29 0.14 0.29 0.11 0.17 0.00 0.20
0.14 0.12 0.12 0.11 0.28 0.18 0.13 0.21 0.15 0.21 0.15 0.73 0.73 0.38 0.11 0.68
0.11 0.73 0.19 0.52 0.73 0.66 0.13 0.67 0.29

16 0.19 0.05 0.22 0.11 0.02 0.07 0.23 0.05 0.30 0.11 0.32 0.18 0.32 0.11 0.25
0.40 0.16 0.13 0.38 0.13 0.38 0.26 0.21 0.38 0.39 0.21 0.39 0.18 0.23 0.00 0.08
0.22 0.12 0.22 0.27 0.28 0.23 0.12 0.15 0.19 0.14 0.09 0.76 0.76 0.36 0.11 0.73
0.11 0.73 0.19 0.56 0.71 0.68 0.21 0.67 0.34

17 0.21 0.05 0.14 0.22 0.02 0.22 0.23 0.05 0.30 0.18 0.22 0.21 0.32 0.19 0.14
0.31 0.13 0.14 0.31 0.13 0.32 0.26 0.16 0.17 0.30 0.16 0.30 0.15 0.19 0.00 0.08
0.15 0.04 0.15 0.27 0.28 0.20 0.15 0.15 0.22 0.14 0.15 0.73 0.73 0.73 0.12 0.69
0.13 0.73 0.26 0.57 0.62 0.73 0.14 0.43 0.46

18 0.18 0.05 0.10 0.21 0.03 0.23 0.23 0.05 0.29 0.31 0.14 0.21 0.14 0.13 0.13
0.35 0.14 0.18 0.34 0.17 0.35 0.28 0.16 0.22 0.34 0.17 0.34 0.17 0.18 0.00 0.17
0.32 0.04 0.28 0.27 0.28 0.19 0.14 0.13 0.29 0.05 0.11 0.69 0.69 0.24 0.12 0.68
0.13 0.68 0.19 0.44 0.64 0.59 0.13 0.41 0.28

19 0.30 0.05 0.12 0.19 0.03 0.10 0.23 0.05 0.31 0.11 0.14 0.23 0.14 0.11 0.10
0.24 0.24 0.09 0.24 0.08 0.26 0.28 0.12 0.20 0.22 0.10 0.22 0.14 0.31 0.00 0.17
0.21 0.04 0.08 0.27 0.28 0.31 0.09 0.13 0.22 0.05 0.09 0.75 0.75 0.35 0.75 0.47
0.75 0.71 0.19 0.58 0.67 0.68 0.57 0.68 0.48

20 0.23 0.04 0.03 0.19 0.06 0.15 0.05 0.05 0.29 0.22 0.27 0.28 0.05 0.15 0.13
0.31 0.31 0.15 0.31 0.12 0.31 0.28 0.15 0.16 0.31 0.14 0.31 0.17 0.20 0.00 0.15
0.27 0.14 0.13 0.15 0.28 0.22 0.15 0.20 0.24 0.12 0.19 0.67 0.67 0.67 0.10 0.67
0.10 0.67 0.27 0.51 0.46 0.67 0.24 0.61 0.43

21 0.16 0.02 0.32 0.12 0.07 0.10 0.03 0.00 0.21 0.21 0.32 0.14 0.32 0.10 0.13
0.29 0.29 0.13 0.31 0.13 0.28 0.28 0.16 0.15 0.29 0.15 0.29 0.14 0.17 0.00 0.10
0.12 0.14 0.11 0.08 0.28 0.19 0.15 0.27 0.16 0.21 0.07 0.69 0.51 0.41 0.15 0.67
0.15 0.69 0.14 0.53 0.51 0.50 0.37 0.50 0.36

Coupling Ratios

ACT	EVTIR	RFTIR	EVKIR	RFAKIR
1	0.43	0.59	0.56	0.77
1	2.16	2.64	1.69	2.07
1	1.05	0.72	3.51	2.39
1	1.35	0.78	2.69	1.55
1	2.43	3.30	7.36	9.98
1	0.81	0.84	0.66	0.68
1	0.56	1.26	0.75	1.68
1	0.40	0.42	1.14	1.20
1	0.75	0.82	2.24	2.46
1	1.10	0.61	1.31	0.73
1	0.48	1.17	1.22	2.97
1	0.42	0.36	0.53	0.46
1	0.52	0.82	0.70	1.10
1	0.40	0.67	1.19	1.99
1	0.49	0.20	3.89	1.57
1	0.63	1.22	1.25	2.42
1	0.17	0.71	0.70	2.87
1	0.69	0.63	0.73	0.67
1	2.48	1.06	0.89	0.38
1	0.11	0.26	0.34	0.81
2	0.52	0.52	1.06	1.06
2	0.57	3.98	0.74	5.12
2	0.83	0.83	1.83	1.82
2	0.73	2.12	1.35	3.90
2	1.09	1.68	1.33	2.04
2	0.85	0.55	0.35	0.23
2	0.83	0.80	2.01	1.94
2	0.64	0.48	1.90	1.44
2	0.63	0.52	0.87	0.71
2	1.27	0.63	1.26	0.62
2	0.40	0.73	0.53	0.97
2	0.31	0.39	0.71	0.86
2	0.31	0.45	0.37	0.53
2	0.59	0.74	0.74	0.93
2	0.42	0.45	0.75	0.80
2	1.24	0.87	1.95	1.36
2	0.38	0.74	0.57	1.11
2	0.07	0.57	0.08	0.62
2	0.29	1.32	0.52	2.33
2	0.17	0.26	0.42	0.63
3	0.68	0.44	0.69	0.44
3	1.73	1.43	2.24	1.43
3	1.40	1.25	2.65	1.25
3	1.30	0.82	3.48	0.82
3	1.37	1.21	4.36	1.21
3	1.73	0.81	1.36	0.81

3	0.58	0.96	1.54	0.96
3	1.45	0.70	4.15	0.70
3	0.86	2.26	1.40	2.26
3	2.18	1.15	4.77	1.15
3	0.72	0.98	2.75	0.98
3	0.29	0.67	0.36	0.67
3	1.49	14.02	0.96	14.02
3	0.77	1.10	1.63	1.10
3	0.44	0.77	1.10	0.77
3	0.88	1.50	1.32	1.50
3	0.23	0.71	1.21	0.71
3	0.44	0.87	0.59	0.87
3	1.60	2.52	1.52	2.52
3	0.42	1.00	0.89	1.00
4	0.44	0.37	0.05	0.05
4	0.25	0.60	0.29	0.69
4	0.57	0.74	0.20	0.26
4	0.17	0.71	0.31	1.29
4	1.21	1.30	2.00	2.14
4	0.66	0.89	0.72	0.97
4	0.64	1.41	2.64	5.79
4	0.45	0.48	0.60	0.65
4	0.66	0.74	0.31	0.35
4	0.52	0.43	1.28	1.07
4	0.34	0.58	0.50	0.85
4	0.23	0.34	0.34	0.50
4	0.33	0.37	0.43	0.49
4	0.46	0.44	0.94	0.90
4	1.18	1.07	0.45	0.41
4	0.24	0.84	0.54	1.86
4	1.64	1.66	0.96	0.97
4	0.31	0.92	0.46	1.33
4	0.65	1.74	1.14	3.02
4	0.43	0.53	1.03	1.27

BIOGRAPHICAL SKETCH

Christopher J Hass was born on April 13, 1973 to his parents Graydon and Lonnie Hass in New Orleans, Louisiana. He has two older brothers, Jay and Jeff. Chris lived in Slidell, Louisiana throughout his childhood until he enrolled at Furman University in 1991.

During his time at Furman University, Chris was a varsity athlete and double majored in Biology and Health and Exercise Science. An interest in the study of human physiology and movement science led Chris to pursue a Master's degree in Exercise Physiology at the University of Florida. A quest for interesting coursework and an interest in clinical movement led him to the Biomechanics Laboratory at the University of Florida and eventually to doctoral work. A combination of new academic information and clinical experiences provided the foundation for his dissertation.

Chris will continue his research training as he has accepted a postdoctoral fellowship in the Department of Neurology at Emory University.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

John W. Chow, Co-chair
Associate Professor of Exercise and Sport Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

James H. Cauraugh, Co-chair
Associate Professor of Exercise and Sport Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Denis Brunt
Associate Professor of Physical Therapy

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Mark D. Tillman
Assistant Professor of Exercise and Sport Sciences

This dissertation was submitted to the Graduate Faculty of the College of Health and Human Performance and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Dean, College of Health and Human Performance

Dean, Graduate School